Appendix Z. Hydraulic analyses of BOP control system (from Ultra Deep)

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Hydraulic analyses of BOP control system

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HYDRAULIC ANALYSIS
DEEPWATER HORIZON BOP CONTROL SYSTEM
ULTRA DEEP

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1 INTRODUCTION

The following hydraulic analysis was commissioned by the BP DWH investigation team to determine the hydraulic functions under normal and abnormal conditions which might have contributed to the accident on the Deepwater Horizon on 20th of April 2010. The initial task was to build a mathematical simulation model of the BOP ram and annular - functions and see if it is possible to replicate the behaviour seen in pressure logs from the well operation the last 20 minutes before the data was lost as shown in Figure 1).

The following initial scenario was proposed:

Time period	Assumed system behaviour
21:30 - 21:34	Assuming one annular BOP is closed and the BOP pressure increases.
21:34 - 21:36	The annular BOP is partly sealing around the Drill Pipe – well flow and pressure conditions are stable.
21:36 - 21:42	The annular BOP loose the seal. Flow to surface increases and BOP pressure drops.
21:42 - 21:46	One annular BOP is closed again and the BOP pressure starts to increase.
21:46 - 21:47	The annular BOP is partly sealing. Flow and pressure conditions are stable but the flow is higher than last time.
21:47 -	Seal is obtained.

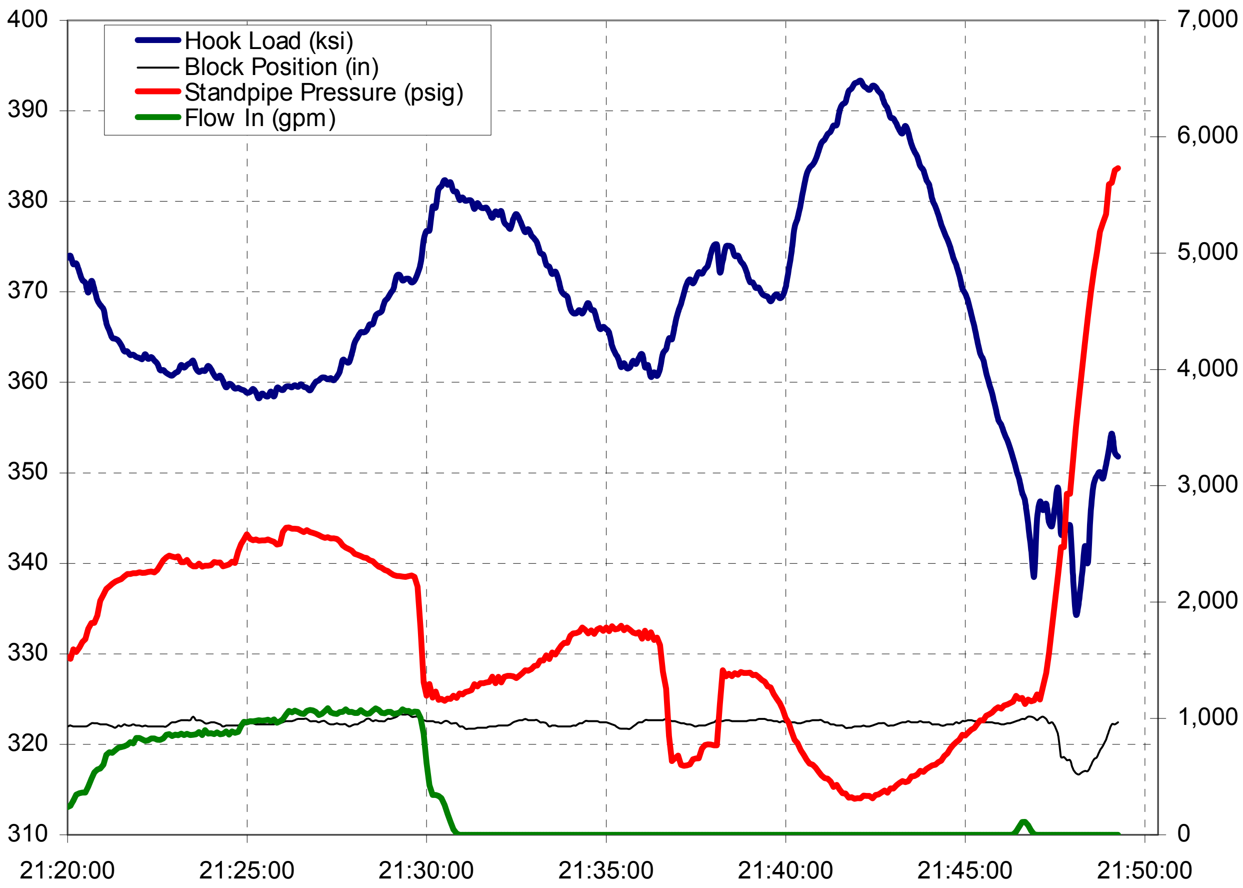


Figure 1) Stand Pipe pressure at surface

The simulation work is performed by Agito AS which is a Norwegian company with more than 15 years of experience from modelling and simulation of subsea control systems for the subsea oil business.

Agito provides their hydraulic analysis services in Houston, Texas, through Ultra Deep LLC. Ultra Deep, which is based in Houston, Texas, is an independent consulting company to the oil and gas industry that specializes in subsea umbilical technologies.

The software that's used is SimulationX which is an object-oriented program for analyzing and optimizing the dynamic behaviour of fluid power components and systems. The program is based on standardized component libraries tailored to subsea control applications. The built-in features of the subsea model elements include non-linear behaviour of valves, mechanical and volumetric efficiency of actuators, complex friction and end stop models, and real gas and fluid behaviour. This allows for non-linear dynamic and flow behaviour of the individual components in the analysis of the complete system interaction. The program applies a variable time-step algorithm in the non-linear differential equations solver.

The following physical effects are included in the mathematical model:

- Pressure loss due to wall friction in lines.
- Pressure loss due to changes in fluid velocity in valves, couplers and fittings.
- Time delay due to wall elasticity in lines combined with fluid elasticity.
- Water depths and local temperature of deployed units.
- Variable external umbilical pressure.
- Pressure and temperature dependent fluid viscosity and Bulk modulus.
- Real gas properties of nitrogen using the modified Bender state equation.

More information about SimulationX and the application of the software to fluid power systems can be found on www.simulationx.com.

1.1 System Description

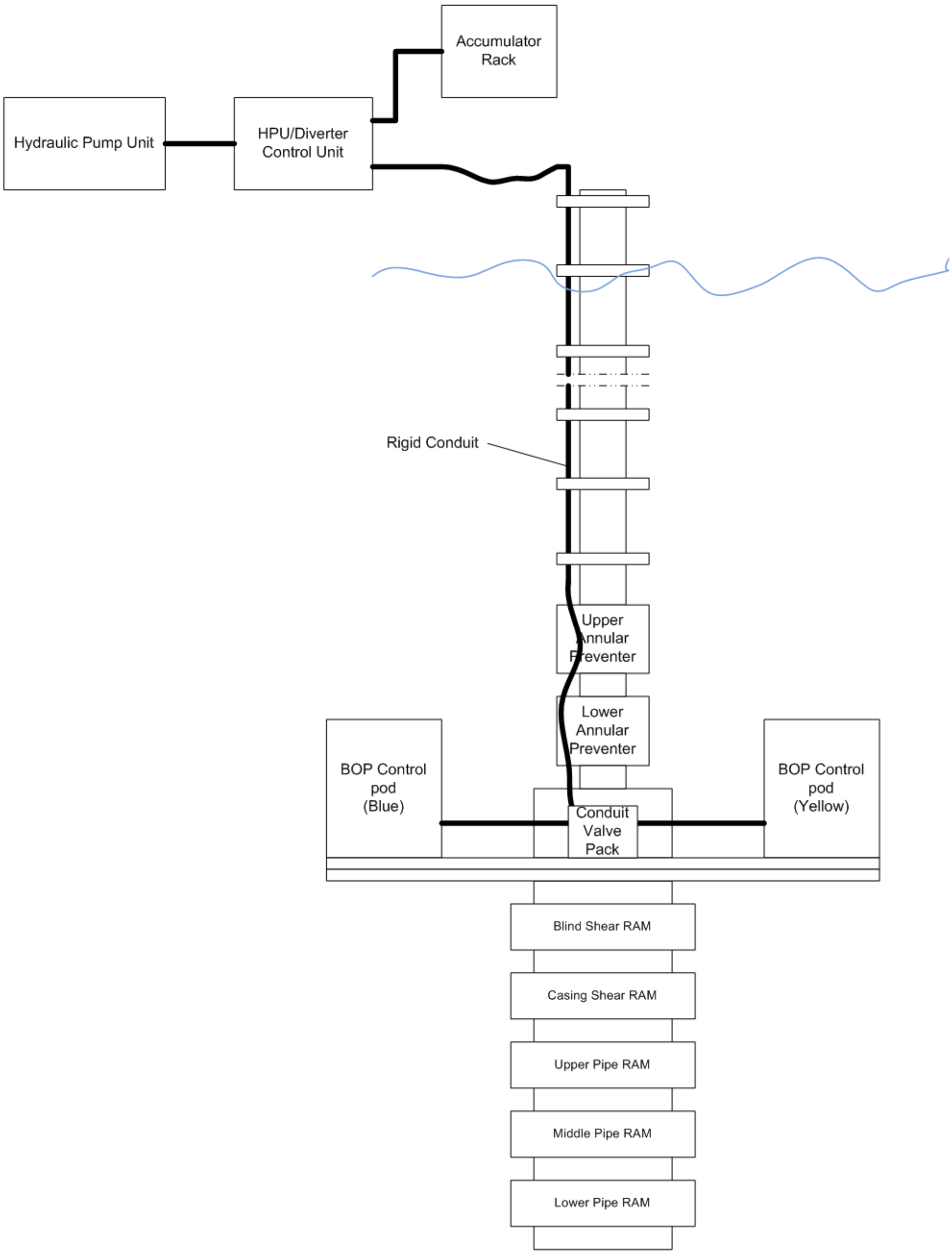


Figure 2) System Sketch

The BOP control system is a deep water system with two electro hydraulic control pods located on the LMRP. Both control pods are energised and communicate with surface system and are updated with the current valve status at all time. Only one pod is active and is the active pod that switches hydraulic fluid to the appropriate actuator when commanded. Hydraulic fluid at 5000 psi is supplied from surface through a Rigid Conduit line and distributed to the “Stack Mounted supply accumulators” and the control pods from the Conduit Valve Pack located on the LMRP.

All stack valves and BOP valves are hydraulically connected to both control pods by tubes and hoses. The control lines from the two pods to the valve actuator are separated with shuttle valves as close to the actuator port as practical possible.

1.2 Abbreviations

The following abbreviations are used in this document:

Abbreviation	Description
BOP	Blow Out Preventer
BSR	Blind Shear Ram
EDS	Emergence Disconnect System
HPU	Hydraulic Power Unit
ID	Internal Diameter
LAP	Lower Annular Preventer
LMRP	Lower Marine Riser Package
OD	Outer Diameter
UAP	Upper Annular Preventer
VBR	Variable Bore Ram

1.3 Revision History of this document

Revision no.	Descriptions of changes
Revision -	First release.
Revision 1	The following changes are included in this revision: • Replaced Scenario 5 and 6 with a new Scenario 5. - More accurate cutting data and better explanation of the cutting sequence.
Revision 2	The following changes are included in this revision: • Included Case 5-3 in Scenario 5
Revision 3	The following changes are included in this revision: • Included Case 5-1b, Case 5-1c and Case 5-4 in Scenario 5 • Updated the Annular Preventer model with new FEM analysis results. The following cases has been updated with new annular preventer model: - Case 1-1a, b and c - Case 1-3 - Case 1-4 - Case 1-5 - Case 1-6 - Case 1-7 - Case 2-1a and b - Case 2-2 a and b - Case 2-3 a and b - Case 2-4 a and b - Case 2-5 a and b Cases for Scenario 3 and 4 are not updated with new packer model since the model, as it is today, doesn’t have an identified position where the packer reaches the Drill Pipe. • LST-0019 rev. 2 is included as appendix.
Revision 4	The following changes are included in this revision: • Included scenario 6 – Additional simulations
Revision 5	The following changes are included in this revision: • Switched position for Casing and Blind Shear RAM in Figure 2).

2 EXCECUTIVE SUMMARY

The simulations have been initiated to understand the hydraulic system behaviour under normal and abnormal conditions. The models used for these simulations are detailed and gives valuable information of the system behaviour in different operation scenarios. However, due to the lack of detailed engineering information from the control system manufacturer available to the investigation team, there are some parameters that have been determine by measurements taken from available drawings and estimated based on experience from the team members. The models were validated by comparing the responses for opening and closing of BOP actuators to data recorded during BOP commissioning and more recent actuator function tests. Although the results compared favourably in all cases, it is therefore recommended to update the different scenarios continuously as new and more detailed information is available.

The simulation results show that the DWH BOP hydraulic system is robust with high capacity. Simulation scenarios with up to 25% reduced subsea accumulator capacity does not show any signs of performance degradation in the operation of different BOP rams or annular preventers either individually or in parallel operations.

If a system leak is present, the leakage has to be higher than the surface pump capacity to influence on the system performance. However, there are a few exceptions from this. If a leakage occurs in an isolated pilot circuit or other systems that is isolated from the supply system when in operation, a leakage can reduce the system performance considerably.
One of these systems is the EDS system with the “Auto Shear Circuit”. Scenario 5 and 6 of this report discuss this circuit more in detail. In this case a leak was reported in one of the ST-lock lines when a ROV tried to shear and lock the Blind Shear Ram (BSR) after the accident. The leak reported stated “no pressure-build up at maximum flow”. Maximum flow from the ROV was 8 USgal/min. It is obvious that a leakage in the ST-lock line can cause an energy loss which again can prevent the BSR from cutting the drill pipe. Exactly how large the leakage has to be depends on the required force to cut the drill pipe.

One question raised and unanswered during the analysis was if the BSR squeezes the drill pipe but does not cut (or shear), is the actuator stroke long enough to activate the ST-locks and partly lock them? It is recommended to find more technical information about the BSR geometry including the activation of internal sequence valves activating the ST-Locks to give answers on this.

It is also recommended to perform shear tests on drill pipes with the same wall thickness and Yeld to better estimate the required leak rate in one ST-Lock line that can prevent the BSR from shear.

3 SCENARIOS THAT HAVE BEEN INVESTIGATED

3.1 Parallel operations of multiple BOP actuators

One line of enquiry was to determine if the system capacity was capable of operating several actuator functions in parallel. This scenario is to verify if the system capacity as designed was robust.

3.2 Parallel operations of multiple BOP actuators with reduced LMRP accumulator capacity

If the system capacity is found to be acceptable in the scenario described in section 3.1, the same parallel operations shall be performed with reduced LMRP accumulator capacity. Two different sub-scenarios have been identified:

a) Low pre-charge pressure
b) One out of four accumulator bottles out of function (leakage of pre-filled gas)

3.3 High BOP pressure

A future line of enquiry was to determine the sensitivity and response of BOP annular preventers to well bore conditions that were assumed to have been present at the time of the accident. Study of the annular preventer actuator reveals that it is sensitive to the BOP pressure with a closing ratio of approximately 9:1. It is obvious that a high bore pressure could in extreme cases open the annular preventer but the question raised is if it can cause a scenario as seen in Figure 1).

3.4 Closing Annular Preventer with leakage in one close line

There are some indications of a system leakage in the 1 ½” Hose fitting to the UAP close connection. There are no written records of this prior to the accident but there is a report written after the incident saying that the fittings had to be tightened 5 turns before the leakage stopped.

3.5 Operating the EDS/”Auto Shear” system

The investigation found strong indications on that the EDS/”Auto Share” system haven’t worked as intended. There have been signs of leakages in the ST-Lock line and the question raised is how large leakage can the system have and still cut the drill pipe.

3.6 Additional Simulations

The additional simulations shows that the annular preventer is sensitive for high BOP bore pressure due to its closing ratio of 8.7:1. With a BOP bore pressure of 8200 psi is it required with 2000 psi closing pressure to ensure full closing of the packer element.

4 SUMMARY AND RECOMMENDED FURTHER WORK

4.1 Scenario 1: Parallel operations of multiple BOP actuators

This scenario has been simulated without any system failures. The results show that the hydraulic system has capacity to operate several large actuators in series and in parallel. The table below list the cases with some key figures from this scenario.

Table of key results from scenario 1

Case no.	Key Results	Figure	Unit
1-1	• Time to close the annular preventer	17.5	sec
1-1	• Minimum LMRP accumulator pressure when closing one annular preventer	4183	psi
1-1	• Minimum LMRP accumulator volume when closing one annular preventer	78	USgal
1-2	• Time to close one VBR	13.3	sec
1-2	• Minimum LMRP accumulator pressure when closing one VBR	4240	psi
1-2	• Minimum LMRP accumulator volume when closing one VBR	78.5	USgal
1-3	• Minimum LMRP accumulator pressure when closing two annular preventers in series	3795	psi
1-3	• Minimum LMRP accumulator volume when closing two annular preventers in series	74.7	USgal
1-4	• Minimum LMRP accumulator pressure when closing one annular preventer followed by a second annular preventer and a VBR in parallel	1675	psi
1-4	• Minimum LMRP accumulator volume when closing one annular preventer followed by a second annular preventer and a VBR in parallel	57.4	USgal
1-5	• Minimum LMRP accumulator pressure when closing one annular preventer followed by a second annular preventer and two VBR's in parallel	1842	psi
1-5	• Minimum LMRP accumulator volume when closing one annular preventer followed by a second annular preventer and two VBR's in parallel	58.9	USgal
1-6	• Minimum LMRP accumulator pressure when closing two annular preventers and one VBR in parallel	2420	psi
1-6	• Minimum LMRP accumulator volume when closing two annular preventers and one VBR in parallel	59.7	USgal
1-7	• Minimum LMRP accumulator pressure when closing two annular preventers and two VBR's in parallel	2296	psi
1-7	• Minimum LMRP accumulator volume when closing two annular preventer and two VBR's in parallel	57.8	USgal

4.2 Scenario 2: Parallel operations with reduced LMRP accumulator capacity

This scenario has been simulated with two different fault scenarios. The first scenario a) is with reduced pre-charge pressure and the second scenario b) is with 25% reduced subsea accumulator capacity. The results show that the system has capacity to continue the operation in both failure modes. The table below list the cases with some key figures from this scenario.

Table of key results from scenario 2

Case no.	Key Results	Figure	Unit
2-1a	• Minimum LMRP accumulator pressure when closing two annular preventers in series	3714	psi
2-1a	• Minimum LMRP accumulator volume when closing two annular preventers in series	107.9	USgal
2-1b	• Minimum LMRP accumulator pressure when closing two annular preventers in series	3714	psi
2-1b	• Minimum LMRP accumulator volume when closing two annular preventers in series	55.8	USgal
2-2a	• Minimum LMRP accumulator pressure when closing one annular preventer followed by a second annular preventer and a VBR in parallel	2718	psi
2-2a	• Minimum LMRP accumulator volume when closing one annular preventer followed by a second annular preventer and a VBR in parallel	99.3	USgal
2-2b	• Minimum LMRP accumulator pressure when closing one annular preventer followed by a second annular preventer and a VBR in parallel	2691	psi
2-2b	• Minimum LMRP accumulator volume when closing one annular preventer followed by a second annular preventer and a VBR in parallel	47.6	USgal
2-3a	• Minimum LMRP accumulator pressure when closing one annular preventer followed by a second annular preventer and two VBR’s in parallel	2334	psi
2-3a	• Minimum LMRP accumulator volume when closing one annular preventer followed by a second annular preventer and two VBR’s in parallel	95.2	USgal
2-3b	• Minimum LMRP accumulator pressure when closing one annular preventer followed by a second annular preventer and two VBR’s in parallel	2317	psi
2-3b	• Minimum LMRP accumulator volume when closing one annular preventer followed by a second annular preventer and two VBR’s in parallel	43.9	USgal
2-4a	• Minimum LMRP accumulator pressure when closing two annular preventers and one VBR in parallel	2385	psi
2-4a	• Minimum LMRP accumulator volume when closing two annular preventers and one VBR in parallel	96	USgal
2-4b	• Minimum LMRP accumulator volume when closing two annular preventers and one VBR in parallel	2317	psi
2-4b	• Minimum LMRP accumulator volume when closing two annular preventers and one VBR in parallel	44.5	USgal
2-5a	• Minimum LMRP accumulator pressure when closing two annular preventers and two VBR’s in parallel	2385	psi
2-5a	• Minimum LMRP accumulator volume when closing two annular preventer and two VBR’s in parallel	94.5	USgal
2-5b	• Minimum LMRP accumulator pressure when closing two annular preventers and two VBR’s in parallel	2259	psi
2-5b	• Minimum LMRP accumulator volume when closing two annular preventer and two VBR’s in parallel	43.4	USgal

4.3 Scenario 3: High BOP pressure

The simulation scenario with high BOP pressure shows that a high pressure can influence on closing the annular preventer. If this is combined with erosion of the packer/pipe it could result in the surface stand pipe pressure response as seen in Figure 1).
However, with a hydraulic supply pressure at normal working pressure (between 4600 and 5000 psi) the annular preventer regulated closing pressure can be increased fast.

4.4 Scenario 4: Leakage in the hydraulic system

This scenario has been simulated with a leak in the annular preventer close hydraulic line. As the results show, this will influence the closing of the annular preventer since the required close pressure will be lower than regulated pressure. However, the HPU pump capacity is totally 3 x 25 USgal/min and the leak rate must be above this if it shall reduce the capacity of the hydraulic supply system and open the preventer again after a closure.

4.5 Scenario 5: Failure in the EDS (Auto Shear) system

This scenario has been simulated to identify possible failures that can that can prevent the BSR from cutting the drill pipe. The EDS system was activated after the incident and estimated BOP pressure with hydrocarbons in the riser is 1500 psi. Calculated required cutting pressure was found to be 2827 psi + BOP bore pressure.

If a reduction of the number of active accumulator bottles could have caused this failure, the number of bottles had to be reduced from 8 to 3 active bottles.

If a reduced initial accumulated pressure could have caused the failure, the initial pressure had to be reduced from 5000 to 3420 psi + static head, ref section

There was not possible to simulate a “shear-failure” due to a leakage in the ST-Lock line under these conditions. A “failure to shear” could be simulated when the input conditions were changed to 4200 psi BOP bore pressure and with a leakage equal to a Cv of 3.

4.6 Recommended further work

The simulation modelling is mostly based on hydraulic schematics, general arrangement drawings and experience data. The model should be updated with correct piping and component Cv values when this is made available.

The annular preventer model is 100% modelled from general arrangement drawings/sketches and assumptions. Since this is the main focus element in this work, this model should be updated with correct geometrical dimensions and test data to have correct model of the packer element stiffness. If possible, resulting erosion/”packer washout” should also be included in the model.
The packer element stiffness used in the updated model is found from FEM analysis. These results seems to be representing the element behaviour good but one question is how the element behaviour is when the packer seals around the drill pipe with a differential pressure across the packer element. This might be important to look deeper in to if the annular preventer is identified to be one of the elements that caused the incident.

It is recommended to maintain the simulation models with new data/parameters as soon as this is available and then update the simulations.

One question raised but unanswered during this analysis is if the BSR squeeze the drill pipe but not cut, is the actuator stroke long enough to activate the ST-locks and partly lock them? It is recommended to find more technical information about the BSR geometry including the activation of internal sequence valves activating the ST-Locks to give answers on this.

It is also recommended to perform shear tests on drill pipes with the same wall thickness and Yeld to better estimate the required leak rate in one ST-Lock line that can prevent the BSR from shear.

5 DETAILED RESULTS WITH TIME PLOTS

5.1 Scenario 1 – Parallel operations of multiple BOP actuators

The scope of this scenario is to verify the capacity of the BOP hydraulic system and investigate the possibilities that the operators activated several functions in parallel which again caused the annular preventer to open.

The scenario of parallel operations has been divided in to 7 cases:

Case 1-1: Closing one annular preventer

Case 1-2: Closing one VBR

Case 1-3: Closing one annular preventer followed by a second annular preventer

Case 1-4: Closing one annular preventer followed by the second annular preventer and one VBR in parallel

Case 1-5: Closing one annular preventer followed by the second annular preventer and two VBR's in parallel

Case 1-6: Closing two annular preventers and one VBR in parallel.

Case 1-7: Closing two annular preventers and two VBR's in parallel.

5.1.1 Case 1-1: Closing one annular preventer

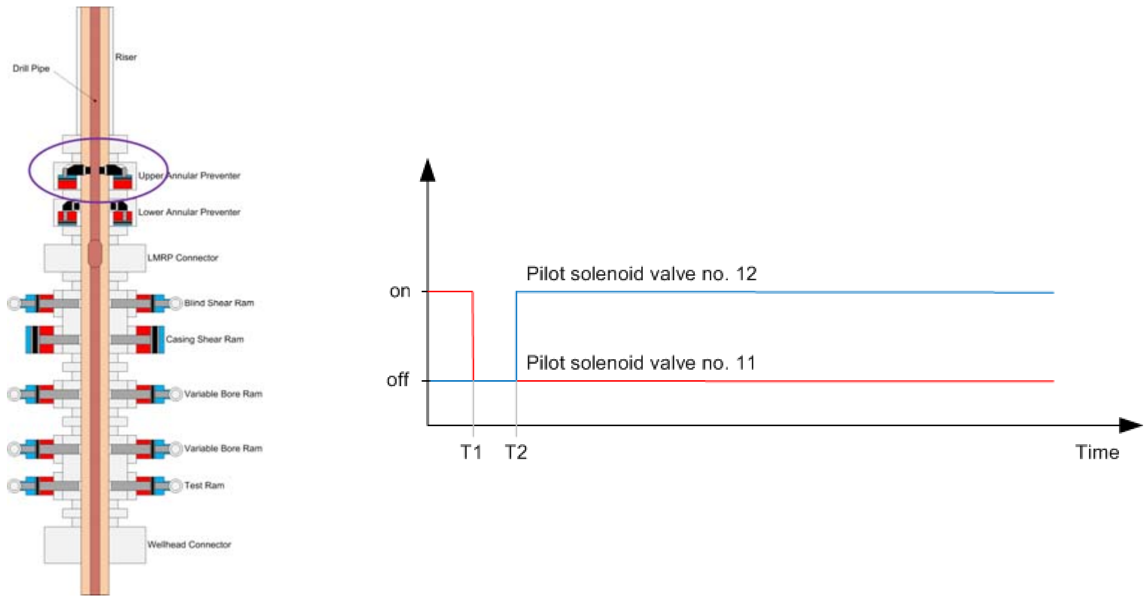


Figure 3) Valve Operation Scheme for Case 1-1

Figure 3) shows the operation of the pilot solenoid valves in the control pod for this case. The time sequence is as follows:

Ident.	Time [sec]	Action
T1	1	Pilot solenoid valve 11 is de-energized to ventilate UAP open line
T2	2	Pilot solenoid valve 12 is energized to pressurize UAP close line

5.1.1.1 Case 1-1a: Closing upper annular preventer (UAP) under normal conditions

The first plot shows the annular preventer actuator stroke together with the pressure reading from the transducer downstream the UAP supply pressure regulator. The pressure regulator is set to 1500 psi + static head (2212 psi)

Solenoid valve no. 12 is energized at t=2 seconds and the 3-way pilot valves shifts to “open” 1.4 seconds later (at t=3.4 s). The annular preventer packer model is set up to close around the pipe at an actuator stroke length of 8.03 inches. That’s where the regulator pressure starts to raise again.

The required closing time from “firing” solenoid valve 12 until the packer element reaches the pipe is simulated to be 17.5 seconds.

This is approximately 7 seconds shorter than the measured time from the offshore test. However, it is chosen to use the model as is since the measured time includes the delay in the control system and the time also depends on the behaviour of the packer element which is an estimated behaviour in this model.

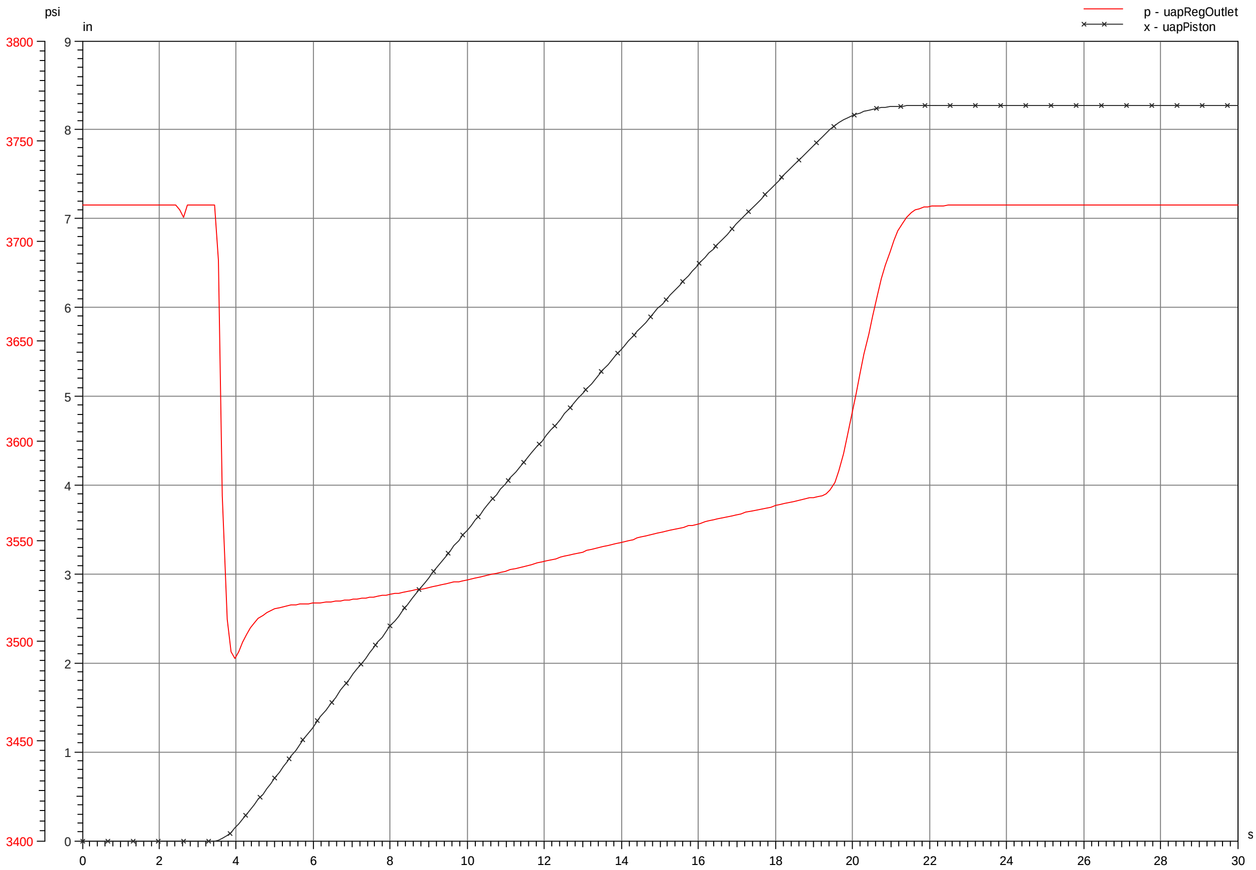


Figure 4) Regulated pressure and annular preventer actuator pos. – Case 1-1a

Legend:	Description	Unit
p - uapRegOutlet	Pressure down stream of the Upper Annular BOP pressure regulator	psi
x - uapPiston	Annular preventer actuator position	in

The LMRP accumulators are pre-charged with nitrogen gas to 4000 psi at 20°C at surface and charged to 5000 psi + static head (2212 psi) by the hydraulics supply subsea. Resulting oil volume in the accumulators at a water depth of 5000 feet and a temperature of 4°C is 84 USgal including 1 USgal dead volume.

When operating one annular preventer, the accumulator volume drops to a minimum of 78 USgal including 1 USgal dead volume before it is replenished from surface.

The supply pressure is initially 7212 psi (5000 psi + static head) and drops to a minimum of 6395 psi (4183 psi + static head) before it raises again.

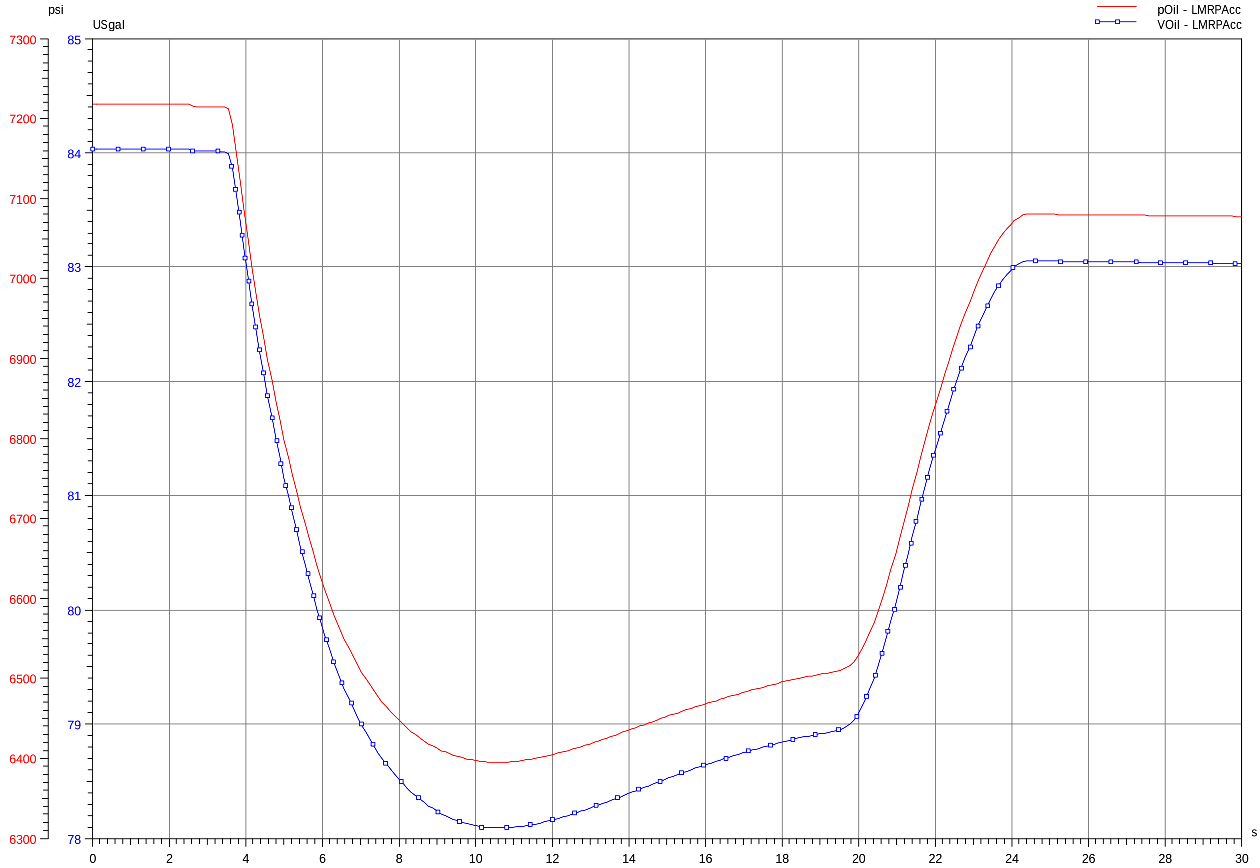


Figure 5) LMRP accumulator pressure and oil volume – Case 1-1a

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 6) shows the pressure trend together with the pump flow for the three surface HPU pumps.

As can be seen, the first pump starts at 14.8 seconds. There is only one pump starting at surface when one annular preventer is operated to close.

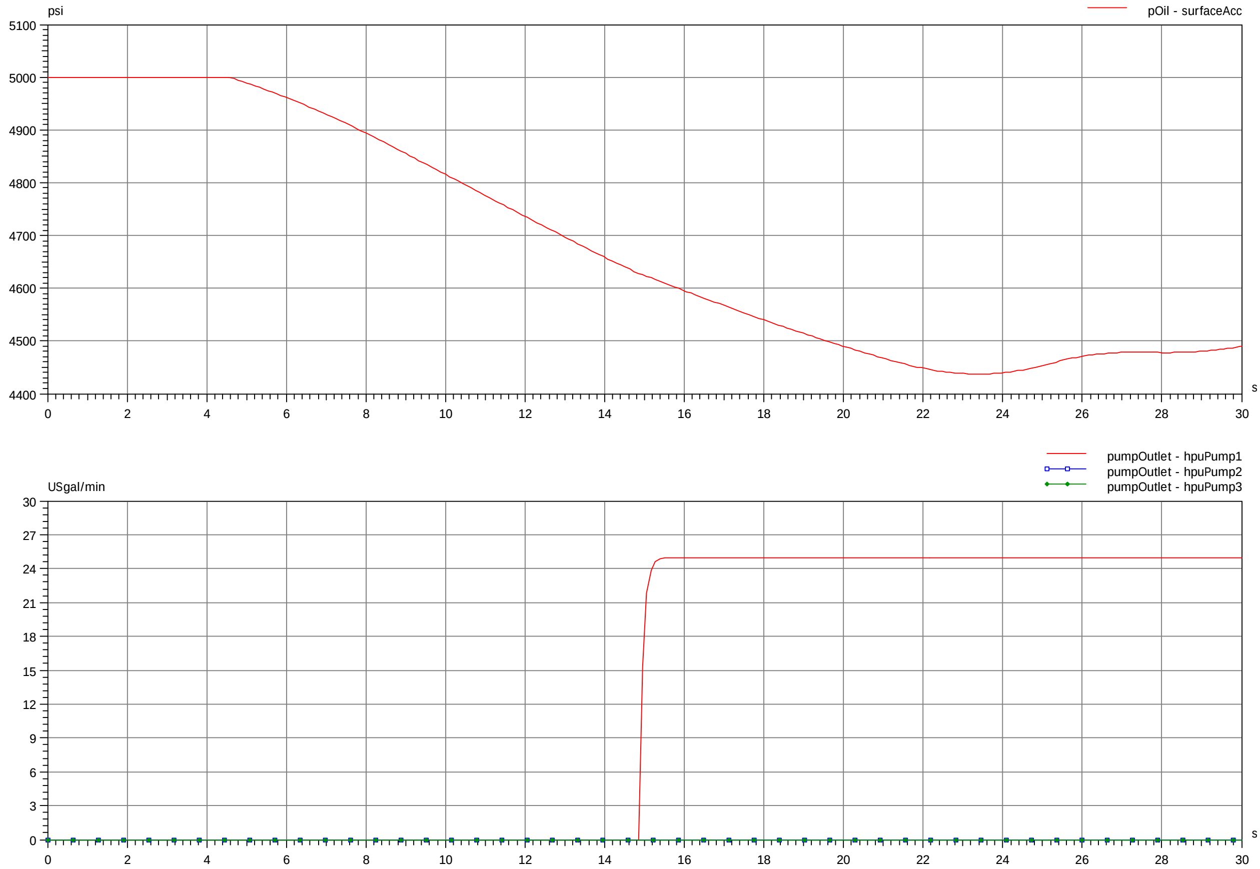


Figure 6) Surface accumulator pressure and pump flows – Case 1-1a

Legend:	Description	Unit
pOil - surface	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.1.1.2 Verification of the annular preventer model

The parameters and assumptions used for the annular preventer model are listed in ref. /1/. This section is to verify the simulated results against these input parameters.

Figure 7) shows the annular preventer closing volume as function of the stroke. As can be seen, the displaced volume at a stroke of 8.03 inches (where the packer reaches the 5 ½" pipe), is simulated to be 46.7 USgal.

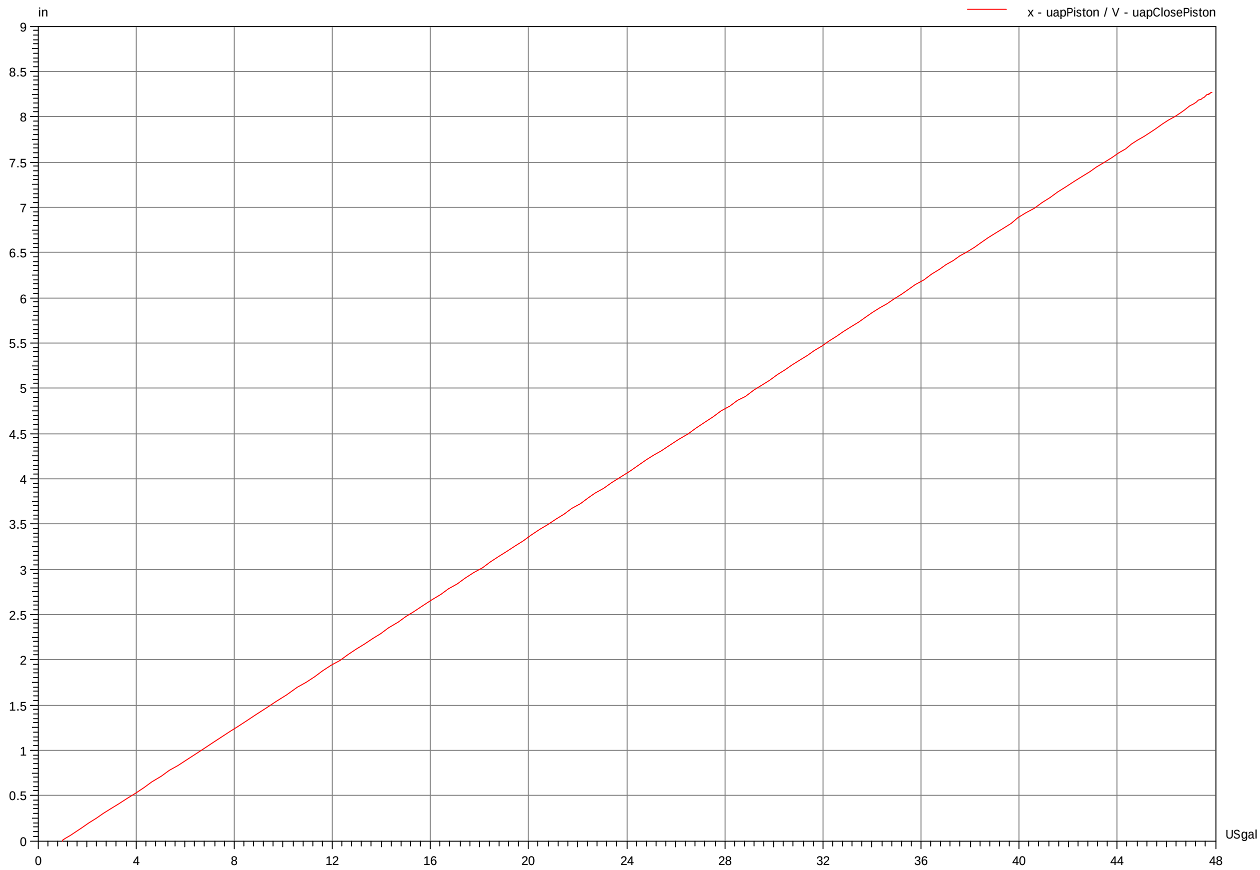


Figure 7) Annular preventer actuator volume as function of stroke

Legend:	Description	Unit
V - uapOpenPiston	Annular preventer open cavity volume	USgal
x - uapPiston	Annular preventer actuator position	in

Figure 8) shows the internal annular preventer actuator force as a function of the actuator stroke. The curve corresponds to the curve in ref. /1/ if the force is divided on the close actuator piston area (1308.67 in^2)

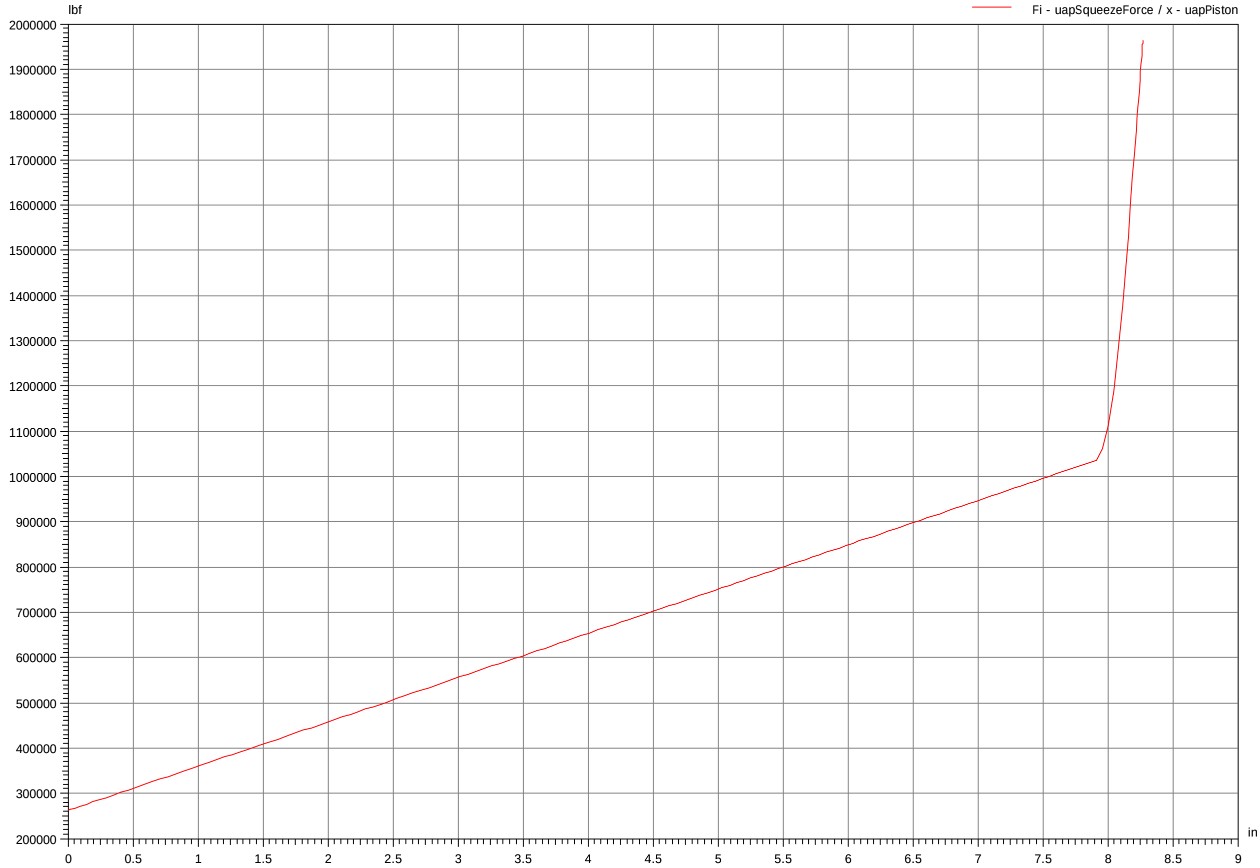


Figure 8) Annular preventer actuator force as function of stroke

Legend:	Description	Unit
Fi - uapSqueezeForce	Annular preventer actuator force	lbf
x - uapPiston	Annular preventer actuator position	in

5.1.1.3 Case 1-1b: Closing UAP with packer elasticity input from FEM analysis

This case is similar as the previous case but the input data for the packer compression force is calculation results from the FEM analysis of the annular preventer. The packer element compression force is given as a function of the actuator stroke as shown in Figure 9) and is inserted to simulationX as an input curve.

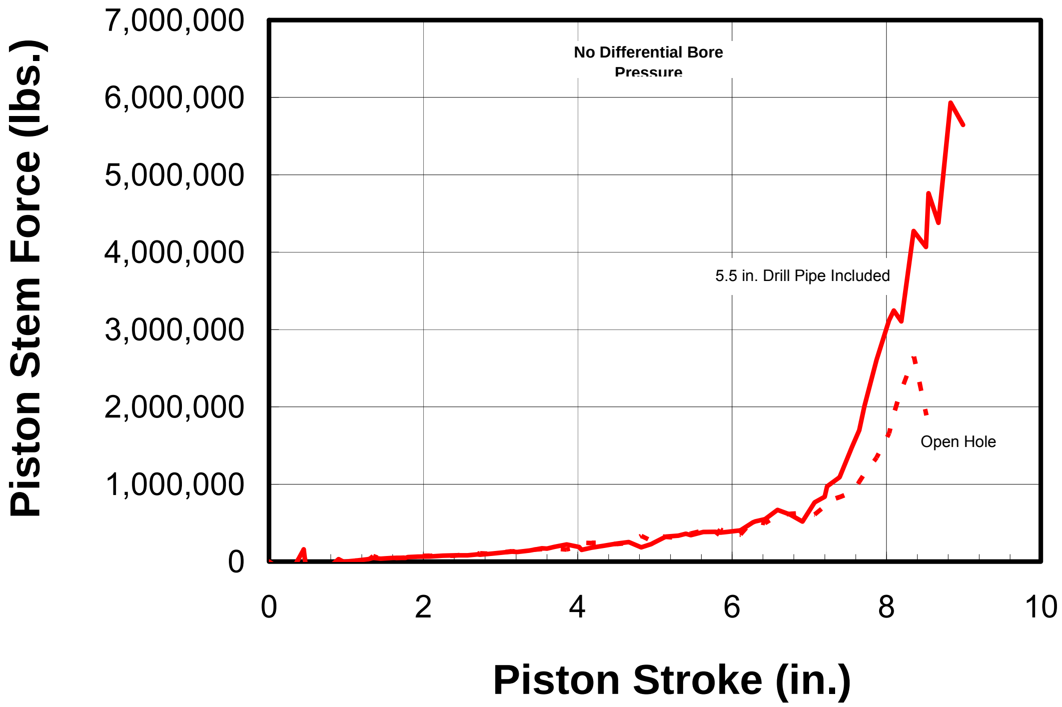


Figure 9) Annular BOP packer compression force input as function of stroke

The expected pressure trend response from a closing sequence of the annular preventer has normally a significant change in the curve slope when the packer element reaches the end stop or the drill pipe wall.
This input curve from the FEM model does not show any significant change in the curve slope and these FEM results are therefore considered not to give behaviour as in the real preventer.

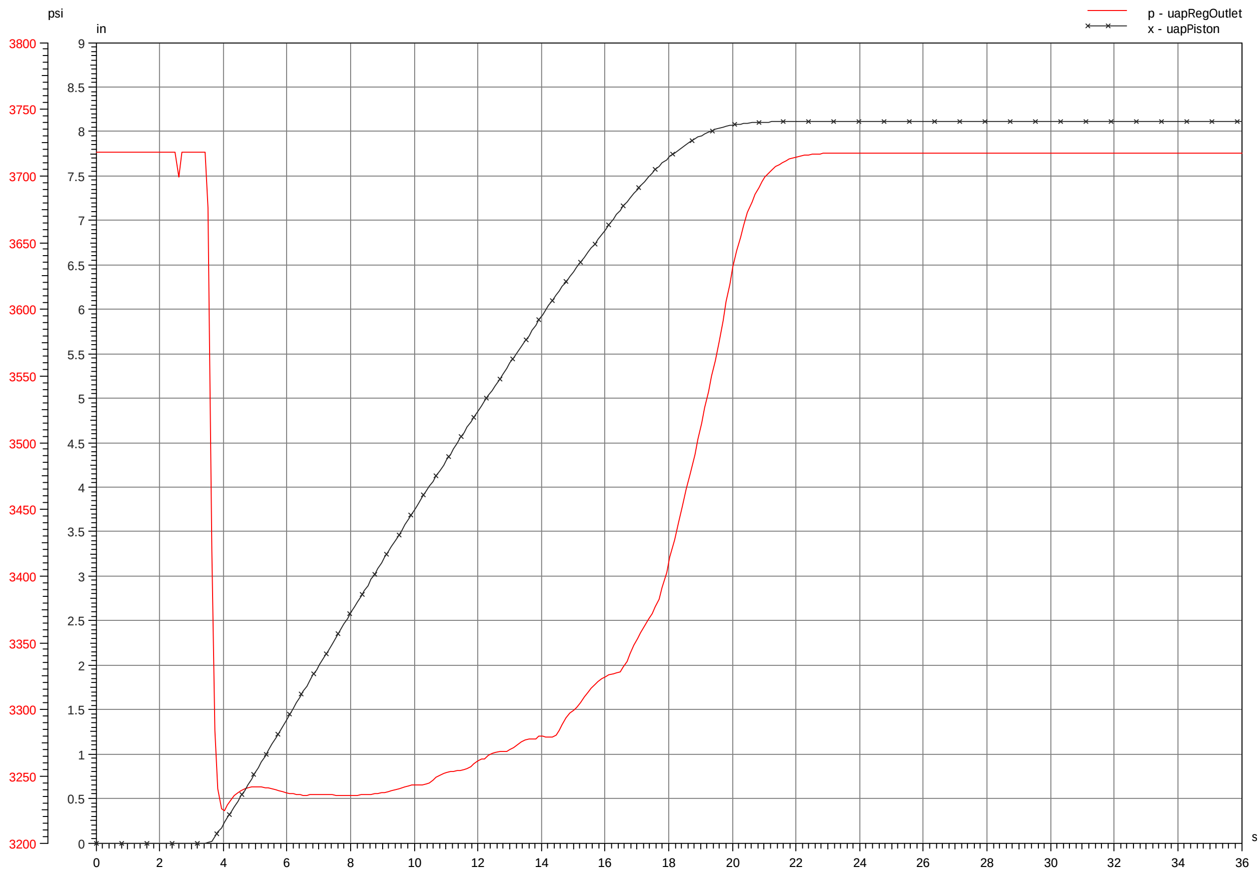


Figure 10) Regulated supply pressure and annular preventer actuator position – Case 1-1b

Legend:	Description	Unit
p - uapRegOutlet	Pressure down stream of the Upper annular preventer pressure regulator	psi
x - uapPiston	Annular preventer actuator position	in

Later, new results from the FEM analysis where presented. These results were divided in different BOP bore pressures as shown in Figure 11).
Note that the results do not include the force from the BOP pressure acting on the activation ring, only compression force for the packer element.

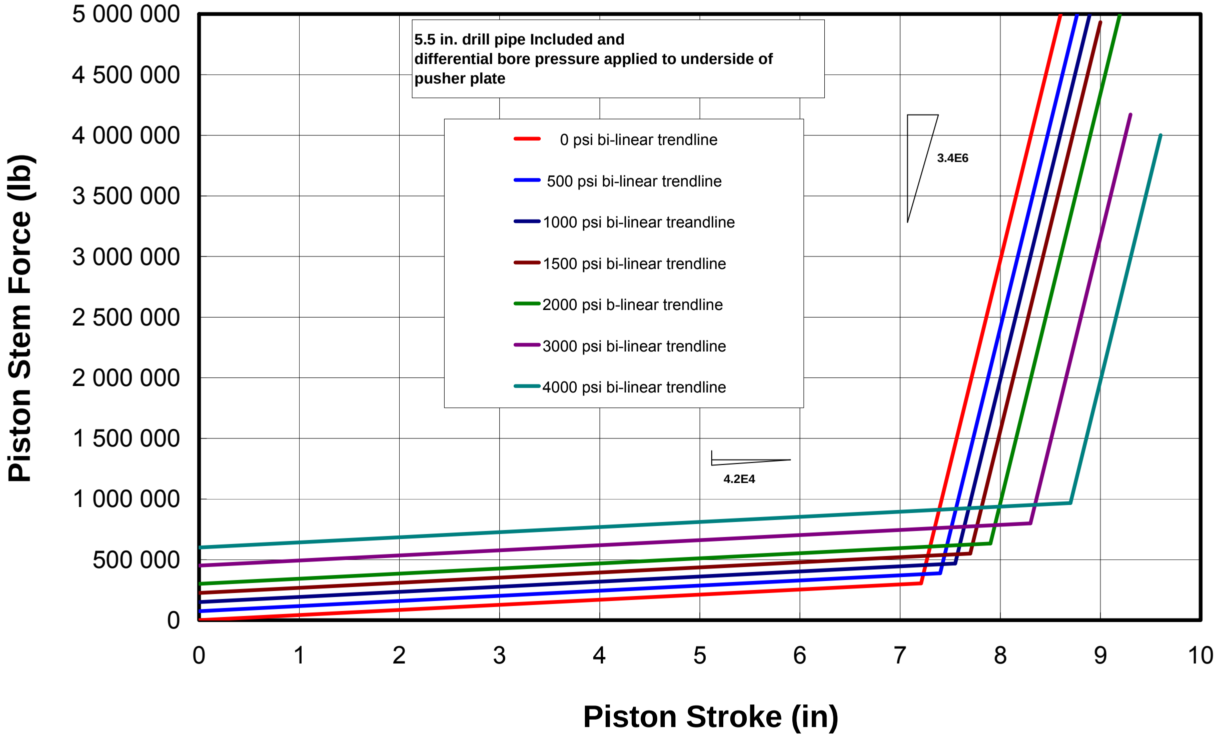


Figure 11) Annular preventer compression force at different BOP bore pressures

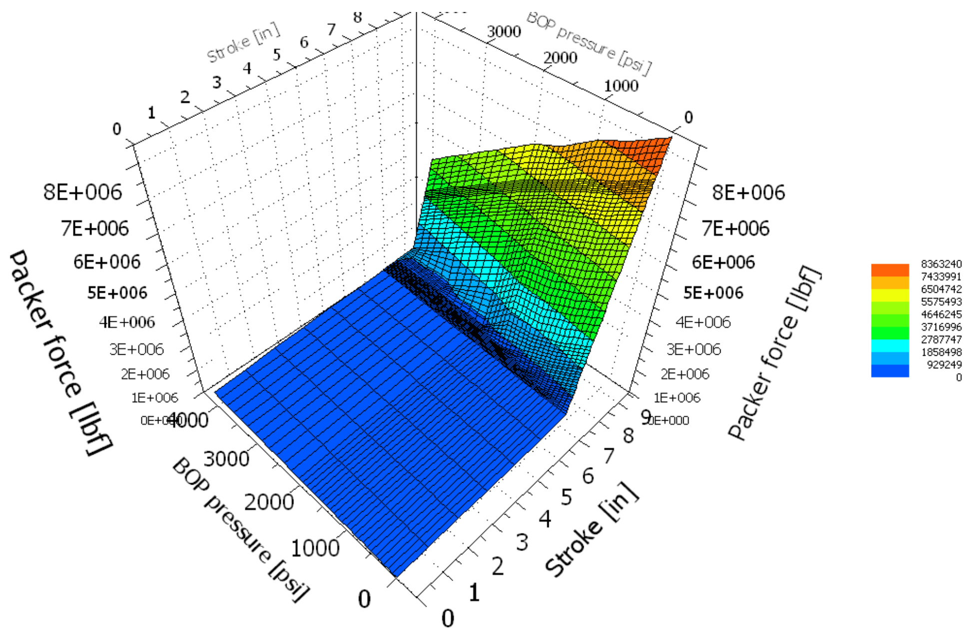


Figure 12) 2D curve input of the “Packer Compression Force”

Figure 12) shows the 2D curve input of the “Packer Compression Force” as it was modelled in SimulationX. All pressure BOP bore pressures was covered in the force input.

This FEM results gives the expected pressure trend in the transducer down stream the pressure regulator.

The required closing time from “firing” solenoid valve 12 until the packer element reaches the pipe is simulated to be 26 seconds which is the same as observed in the offshore test.

The results with the latest FEM analysis results are evaluated to be close to the real packer behaviour. All cases which include annular preventer models have been updated with these new results from revision 3 of this document.

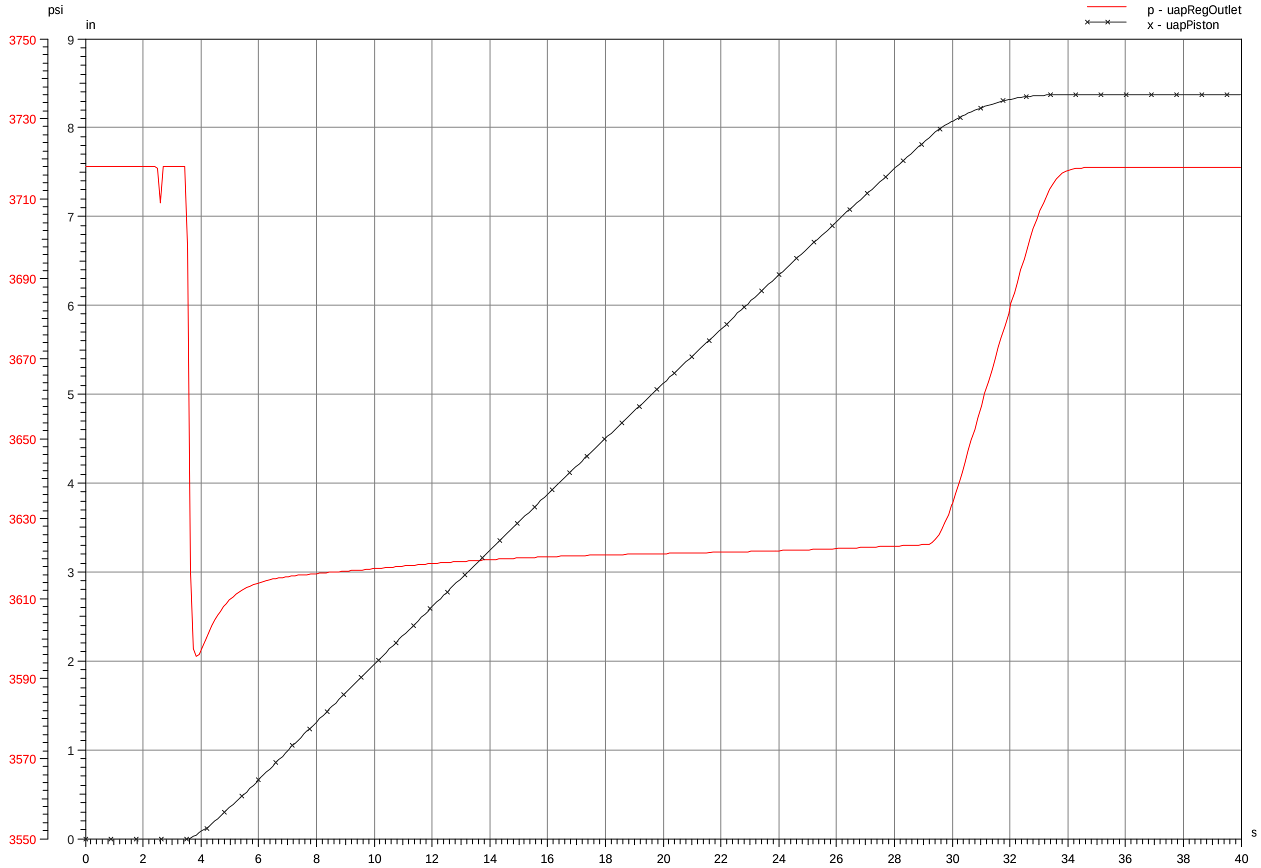


Figure 13) Regulated supply pressure and annular preventer actuator position – Case 1-1b

Legend:	Description	Unit
p - uapRegOutlet	Pressure down stream of the Upper annular preventer pressure regulator	psi
x - uapPiston	Annular preventer actuator position	in

5.1.1.4 Case 1-1c: Operation of UAP with increase of closing pressure

This case shows a closure of one annular preventer followed by an increase of the closing pressure from 1500 psi to approximately 2000 psi (+ static head).

The closing sequence is similar to the two previous cases and at t=40 seconds, solenoid valve 3 opens and pressurizes the pressure regulator pilot port.

As can be seen from Figure 14), it will take some 5 seconds to increase the closing pressure from 1500 psi to 2000 psi (+ static head).

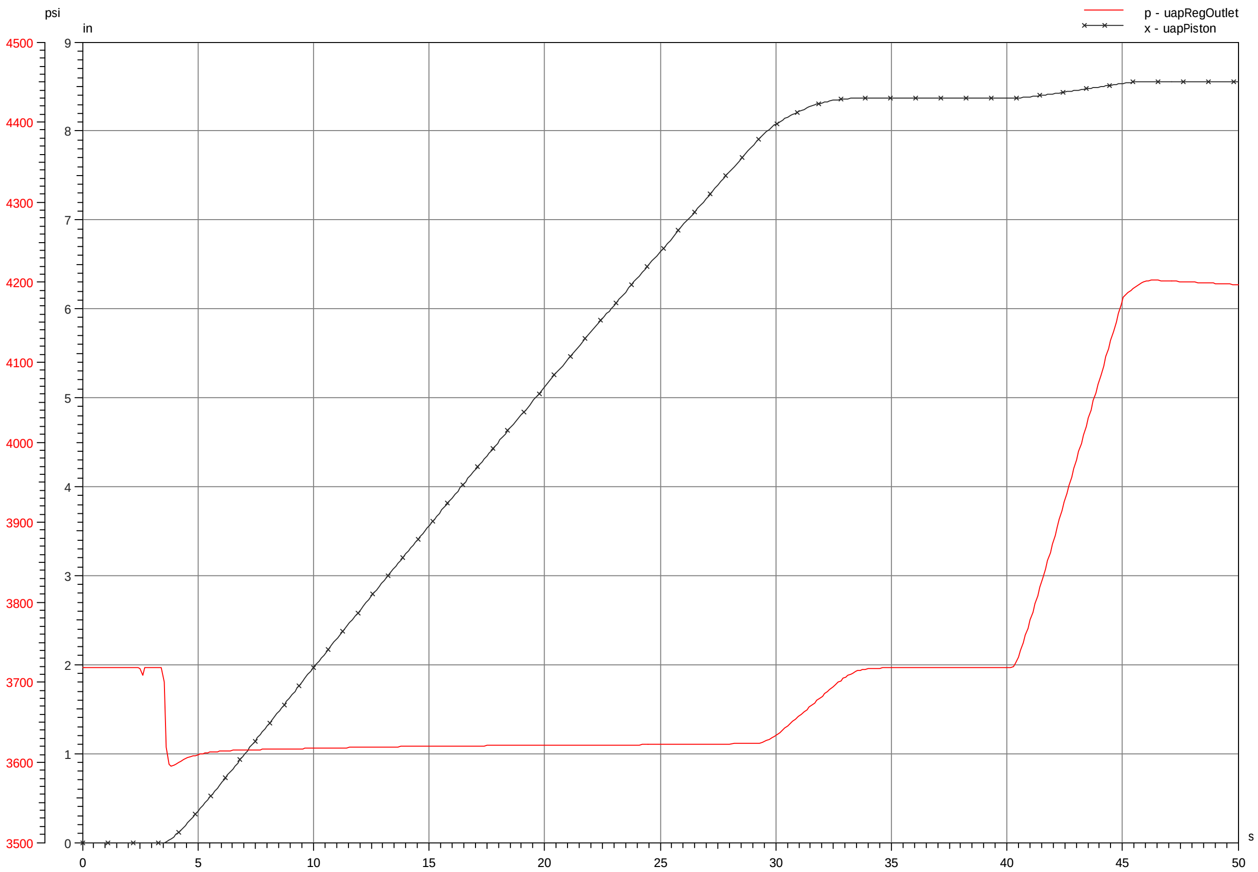


Figure 14) Regulated supply pressure and annular preventer actuator position – Case 1-1c

Legend:	Description	Unit
p - uapRegOutlet	Pressure down stream of the Upper Annular BOP pressure regulator	psi
x - uapPiston	Annular BOP actuator position	in

5.1.2 Case 1-2: Operation of one variable bore ram (VBR)

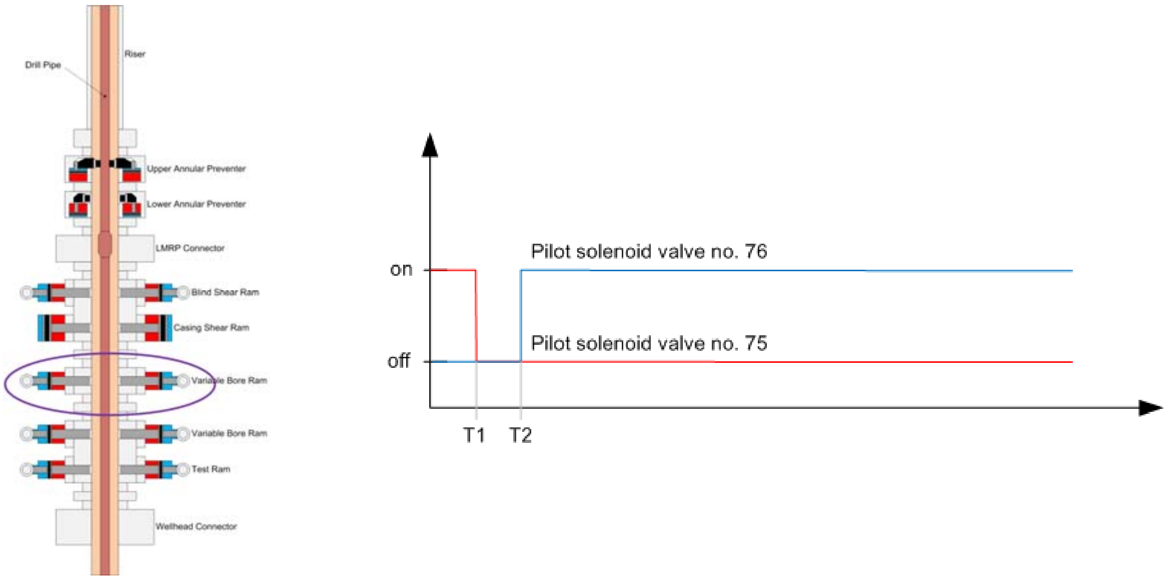


Figure 15) Valve Operation Scheme for Case 1-2

Figure 15) shows the operation of the pilot solenoid valves in the control pod for this case. The time sequence is as follows:

Ident.	Time [sec]	Action
T1	1	Pilot solenoid valve 75 is de-energized to ventilate VBR1 open line
T2	2	Pilot solenoid valve 76 is energized to pressurize VBR1 close line

Figure 16) shows the VBR actuator and ST Lock strokes together with the pressure reading from the transducer downstream the ram supply line pressure regulator. The pressure regulator is set to 3000 psi + static head (2212 psi)

Solenoid valve no. 76 is energized at t=2 seconds and the 4-way pilot valves shifts to "open" 1.4 seconds later (at t=3.4 s).

The required time from "firing" solenoid valve 76 until the VBR ST locks are fully closed is simulated to be 13.3 seconds.

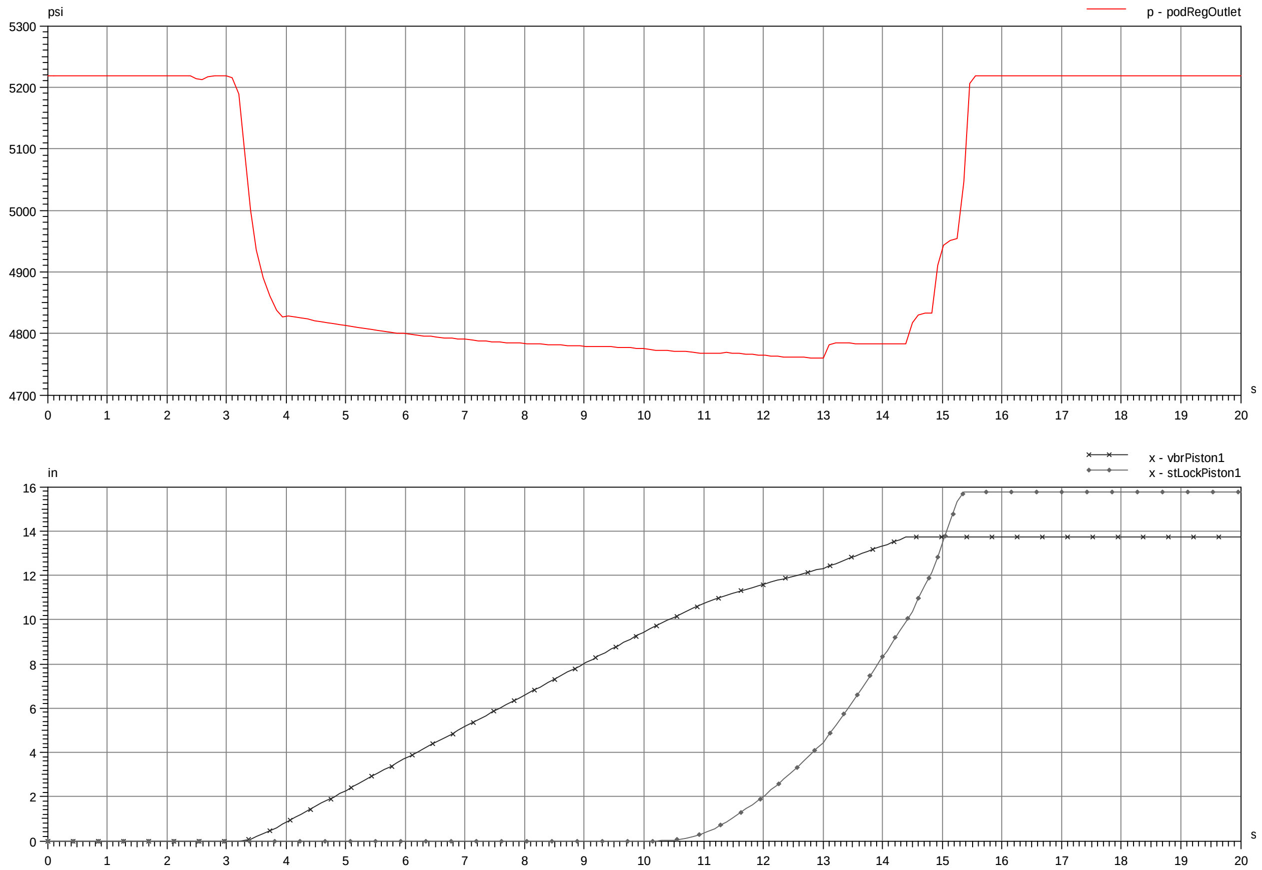


Figure 16) Regulated supply pressure and Annular BOP actuator position – Case 1-2

Legend:	Description	Unit
p - podRegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR actuator position	in
x – stLockPiston1	ST Lock position	in

The LMRP accumulators are pre-charged to 4000 psi with gas at 20°C at surface and charged to 5000 psi + static head (2212 psi) by the hydraulics subsea. Resulting oil volume in the accumulators at a water depth of 5000 feet and a temperature of 4°C is 84 Usgal including 1 USgal dead volume.

When operating one VBR, the accumulator volume drops to a minimum of 78.5 USgal including 1 USgal dead volume before it is fully replenished again from surface.

The supply pressure is initially 7212 psi (5000 psi + static head) and drops to a minimum of 6452 psi (4240 psi + static head) before it raises again.

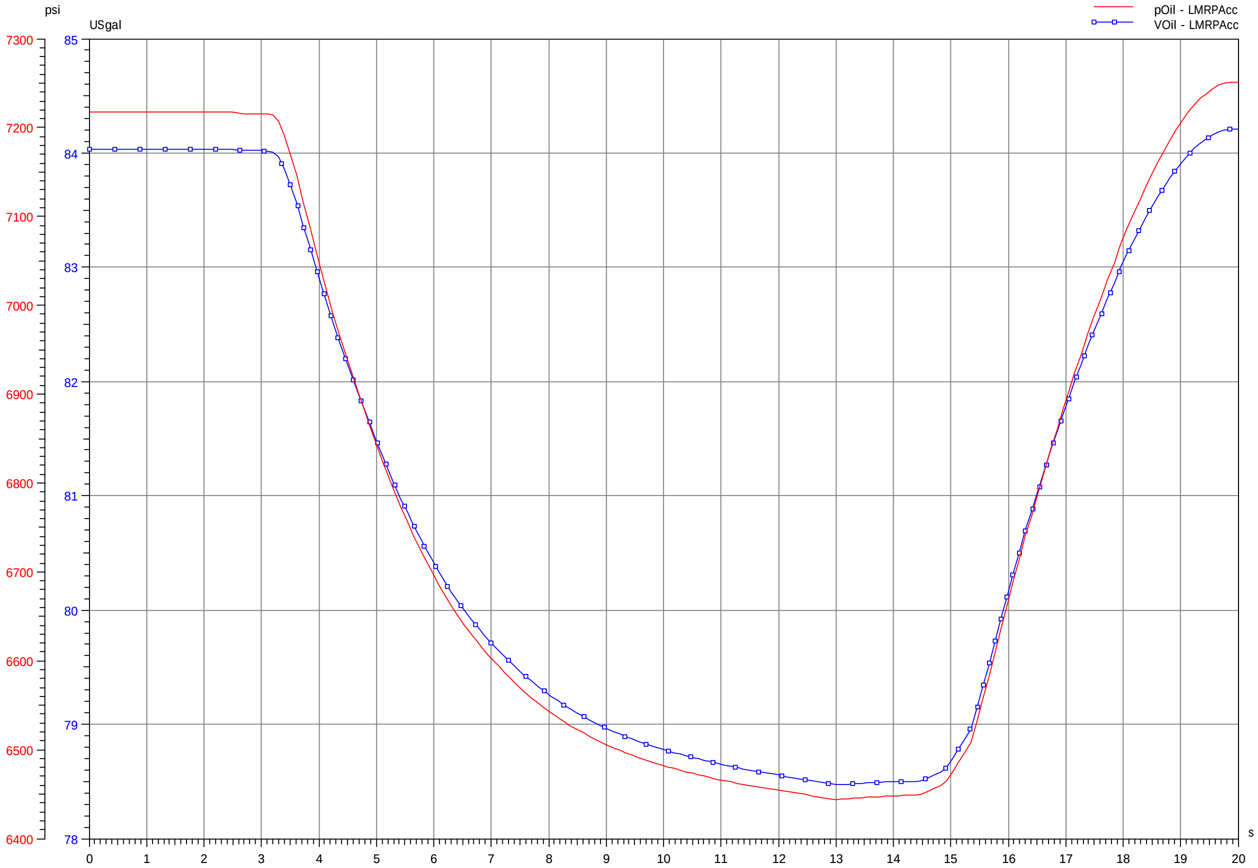


Figure 17) LMRP accumulator pressure and oil volume – Case 1-2

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 18) shows the pressure trend together with the pump flow from the three surface HPU pumps.

As can be seen, the first pump starts at 16.2 seconds. There is only one pump starting at surface when one VBR is operated to close.

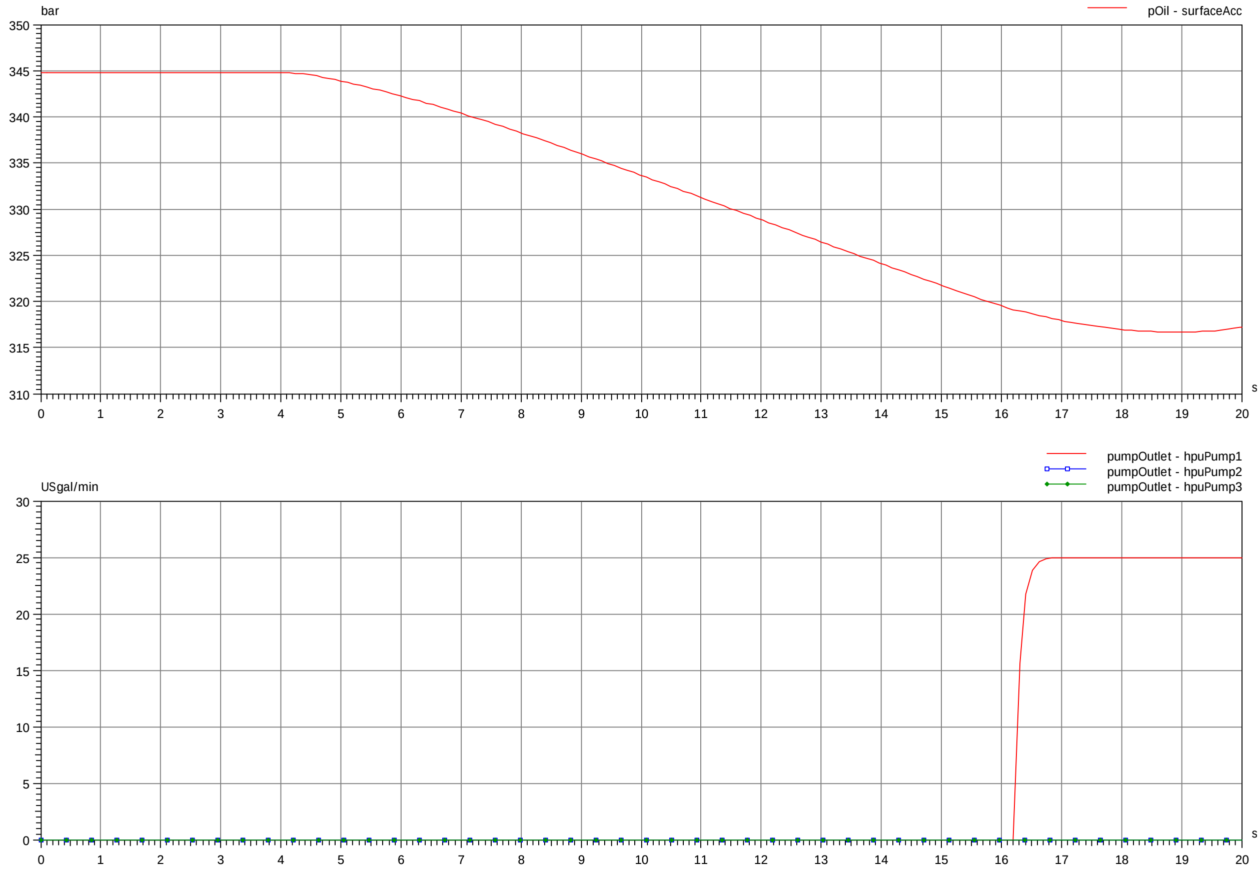


Figure 18) Surface accumulator pressure and pump flows – Case 1-2

Legend:	Description	Unit
pOil - surface	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.1.2.1 Verification of the VBR model

The parameters and assumptions used for the VBR model are listed in ref. /1/. This section is to verify the simulated results against these input parameters.

Figure 19) shows the VBR and ST lock volumes when operating the VBR to Close. As can be seen, the VBR actuator Close volume starts initially at 1 USgal and ends at 13.3 USgal. This gives a volume difference of 12.3 USgal which corresponds with ref. /1/.

The VBR Open volume starts initially at 12.7 USgal and ends at 1 USgal. This gives a volume difference of 11.7 USgal which corresponds with ref. /1/.

The ST Lock volume starts initially at 0.1 USgal and ends at 3.5 USgal. This gives a volume difference of 3.4 USgal which corresponds with ref. /1/.

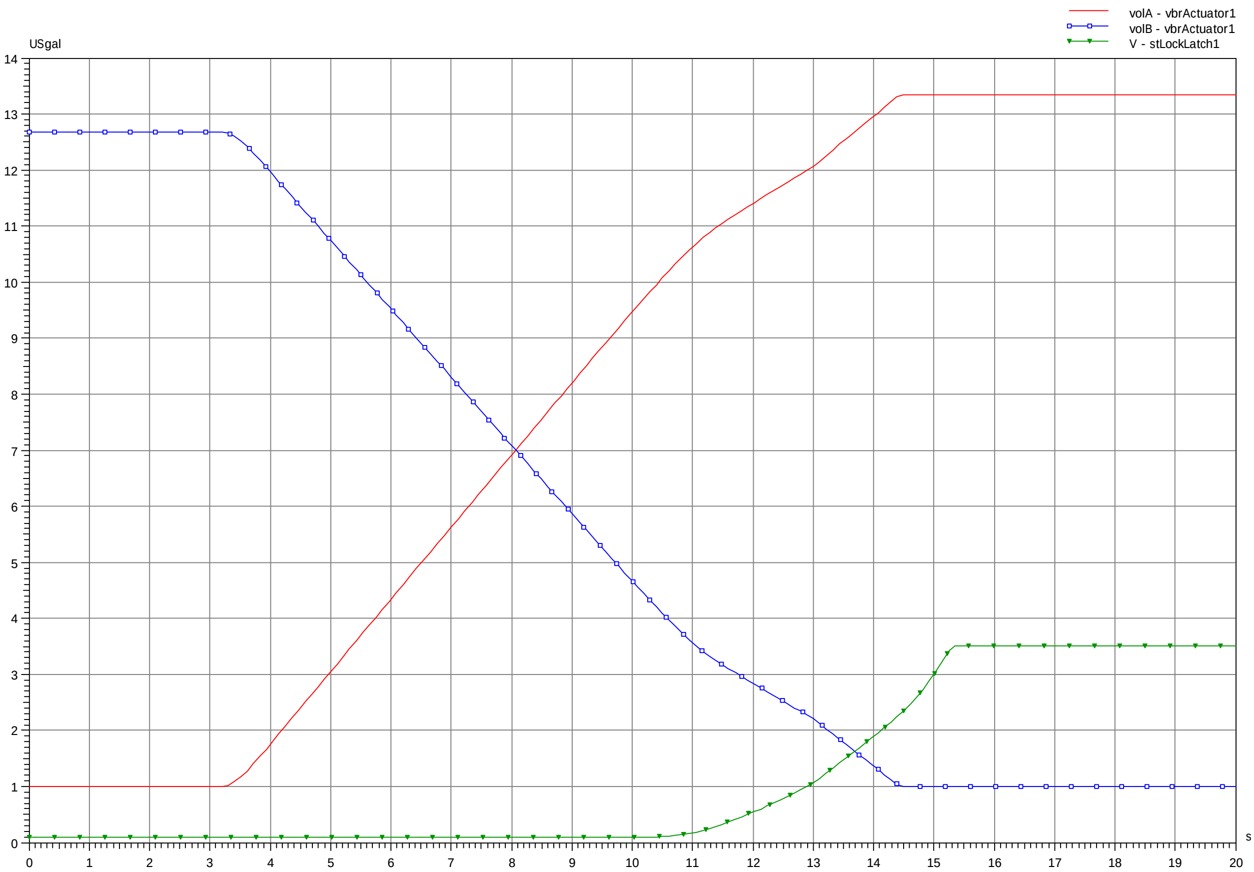


Figure 19) Annular BOP actuator volume as function of stroke

Legend:	Description	Unit
volA – vbrActuator1	VBR closing cavity volume	USgal
volB – vbrActuator1	VBR opening cavity volume	USgal
V – stLockLatch	ST lock latch cavity volume	USgal

5.1.3 Case 1-3: Closing UAP and lower annular preventer (LAP) in series

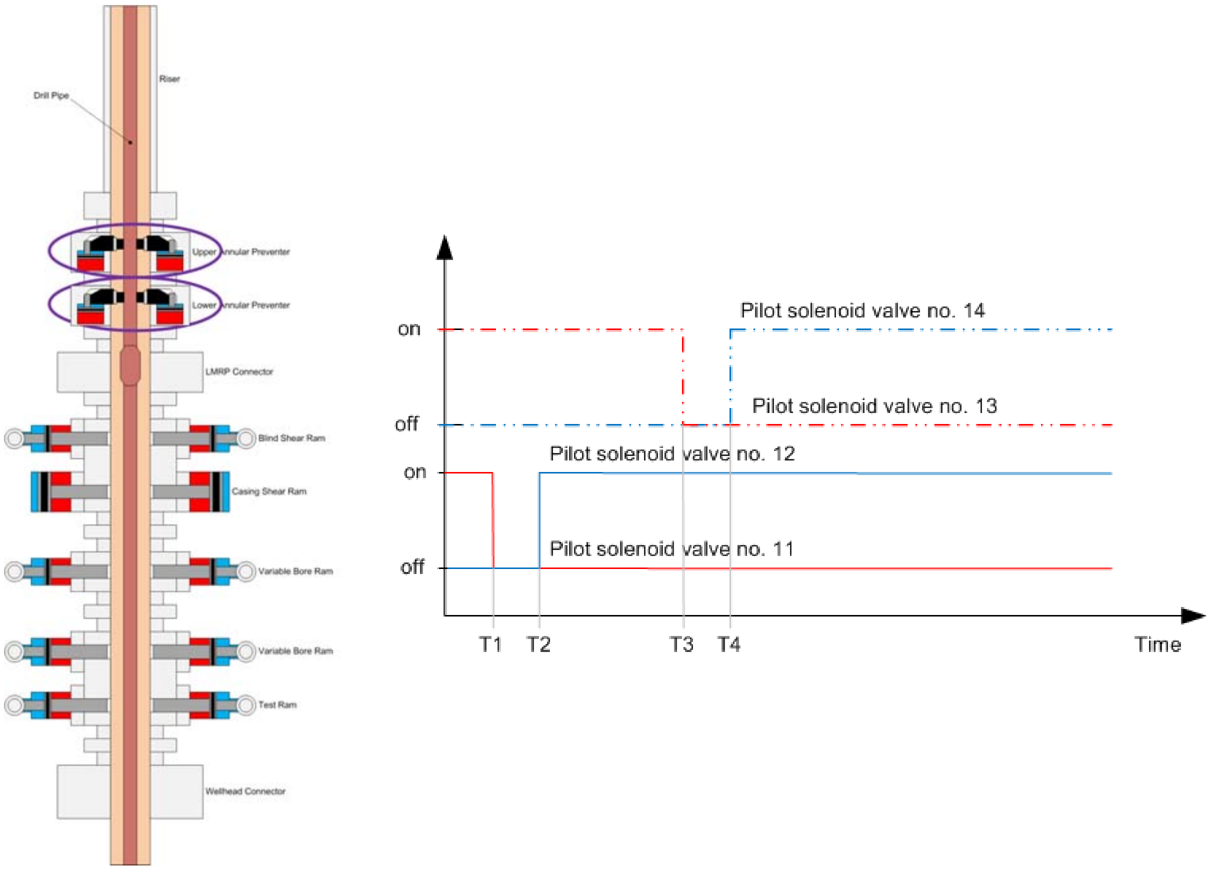


Figure 20) Valve Operation Scheme for Case 1-3

Figure 20) shows the operation of the pilot solenoid valves in the control pod for this case. The time sequence is as follows:

Ident.	Time [sec]	Action
T1	1	Pilot solenoid valve 11 is de-energized to ventilate UAP open line
T2	2	Pilot solenoid valve 12 is energized to pressurize UAP close line
T3	31	Pilot solenoid valve 13 is de-energized to ventilate LAP open line
T4	32	Pilot solenoid valve 14 is energized to pressurize LAP close line

Figure 21) shows the pressure trends and actuator positions for the two annular preventers. The first annular preventer is “fired” to close at 2 seconds and the second at 32 seconds.

Both preventers operate as expected and there is no sign of low capacity in the hydraulic system.

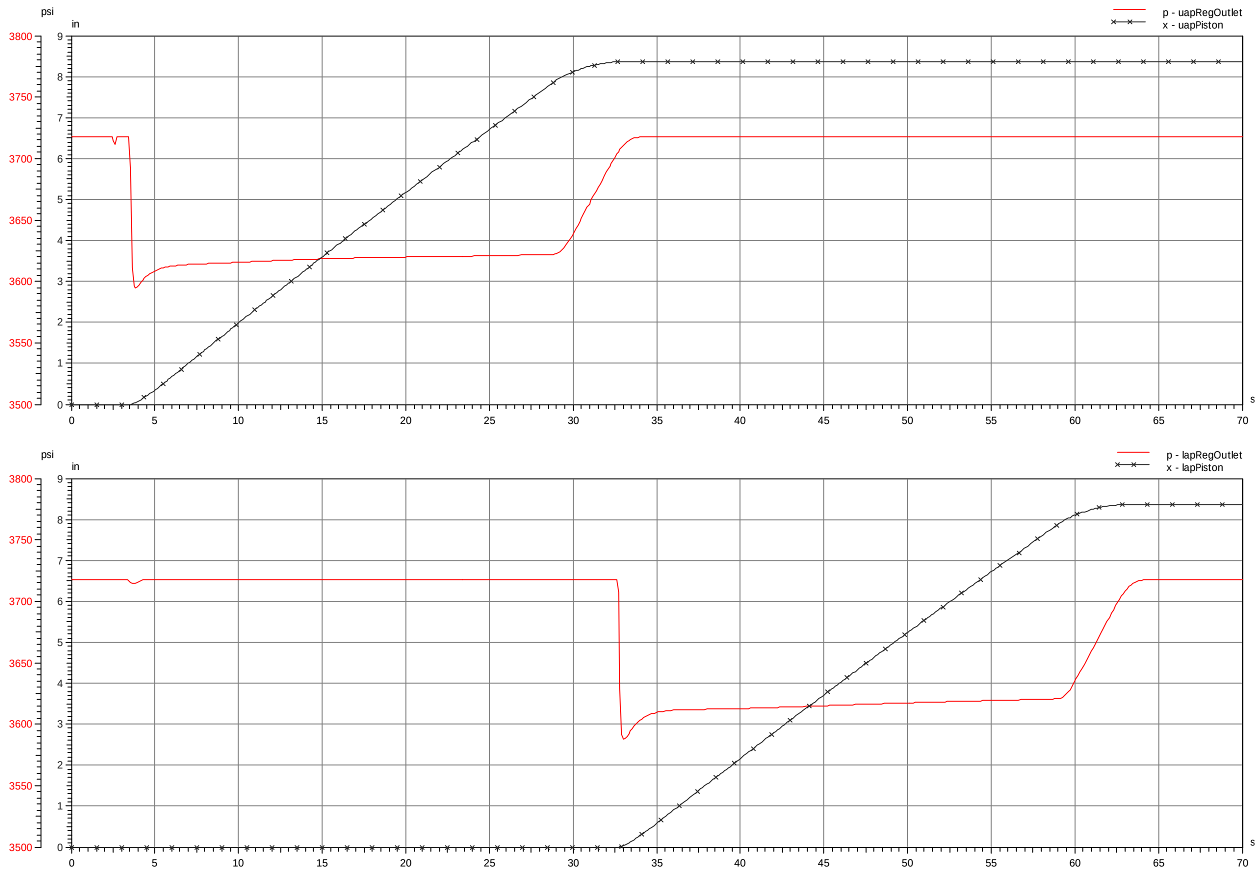


Figure 21) Pressure trends and actuator positions for Case 1-3

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in

When operating the two annular preventers, the LMRP accumulator oil volume drops to a minimum of 77.3 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 6320 psi (4102 psi + static head).

The system pressure is maintained above normal operating pressure for the VBR's (3000 psi + static head) throughout the sequence.

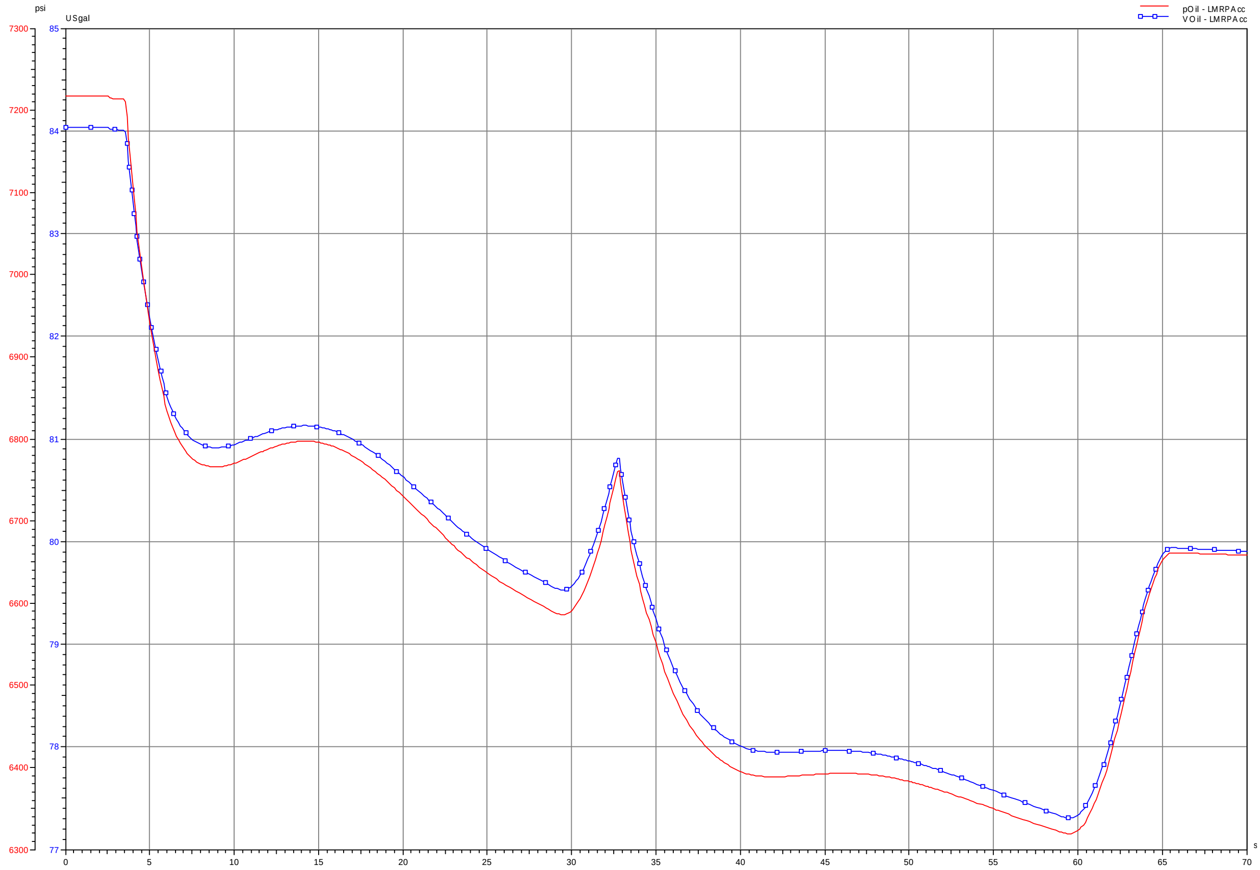


Figure 22) LMRP accumulator pressure and oil volume – Case 1-3

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 23) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while operating two annular preventers in series. As can be seen, the first pump starts at 21 seconds and the second pump starts at 37 seconds.

Minimum surface accumulator pressure is 4203 psi.

Each pump has a flow rate of 25 USgal/min each and together they supply 50 USgal/min to the system.

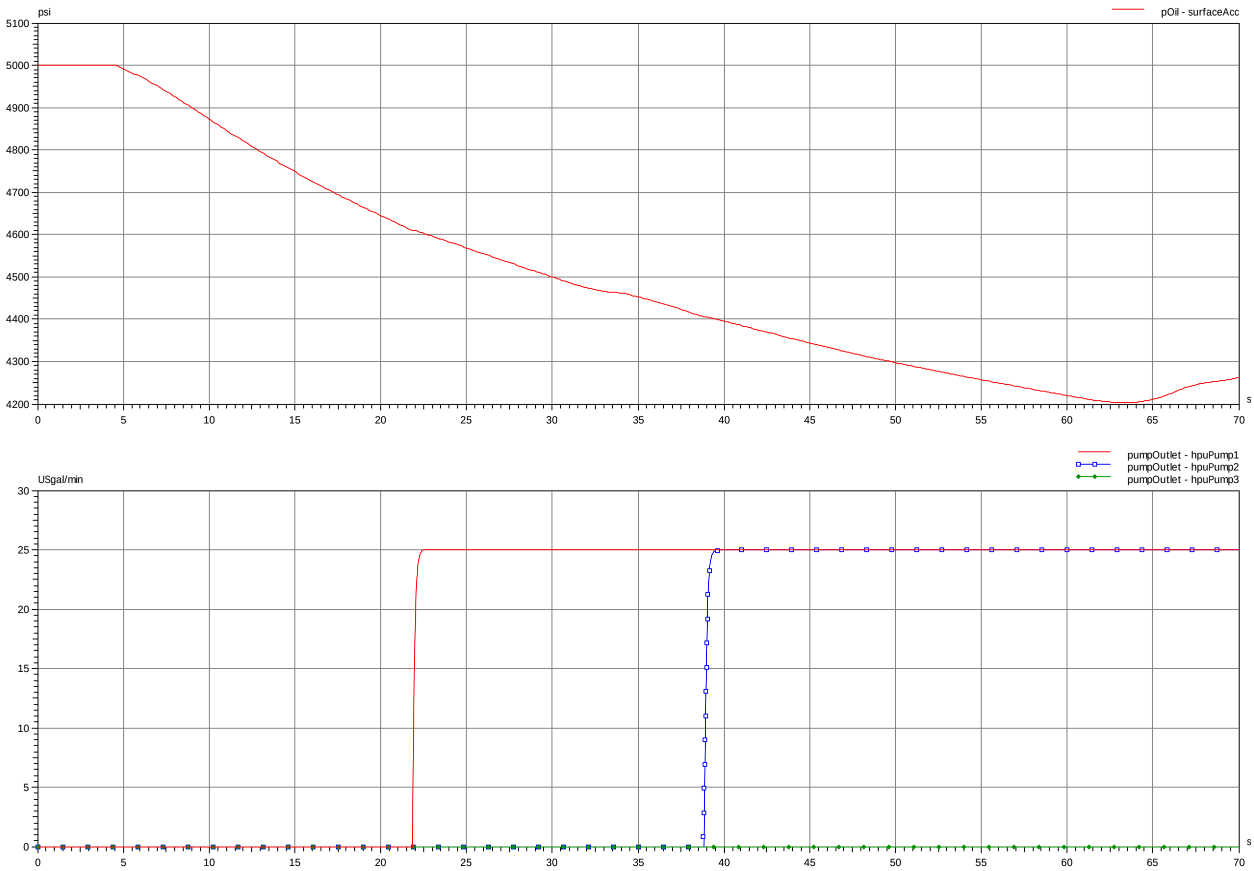


Figure 23) Surface accumulator pressure and pump flows – Case 1-3

Legend:	Description	Unit
pOil - surface	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.1.4 Case 1-4: Closing UAP followed by LAP and one VBR in parallel

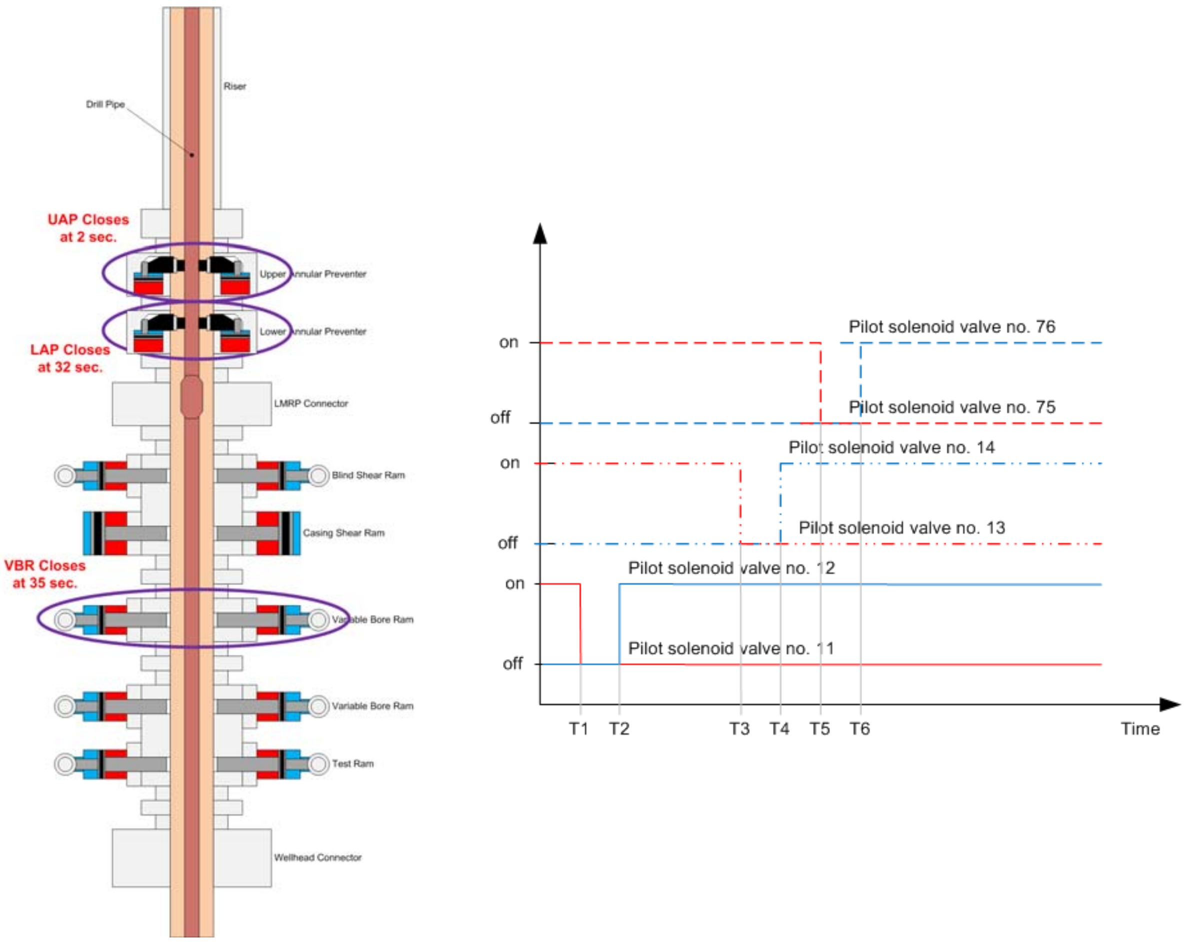


Figure 24) Valve Operation Scheme for Case 1-4

Figure 24) shows the operation of the pilot solenoid valves in the control pod for this case. The time sequence is as follows:

Ident.	Time [sec]	Action
T1	1	Pilot solenoid valve 11 is de-energized to ventilate UAP open line
T2	2	Pilot solenoid valve 12 is energized to pressurize UAP close line
T3	31	Pilot solenoid valve 13 is de-energized to ventilate LAP open line
T4	32	Pilot solenoid valve 14 is energized to pressurize LAP close line
T5	34	Pilot solenoid valve 75 is de-energized to ventilate VBR1 open line
T6	35	Pilot solenoid valve 76 is energized to pressurize VBR1 close line

Figure 25) shows the pressure trends and actuator positions for the two annular preventers and one VBR. The first annular preventer is “fired” to open at 2 seconds, the second annular preventer at 32 seconds and the VBR at 37 seconds. This opening sequence gives a parallel operation between the last annular preventer and the VBR.

All BOP valves operate as expected and there is no sign of reduced system capacity from the valve behaviour.

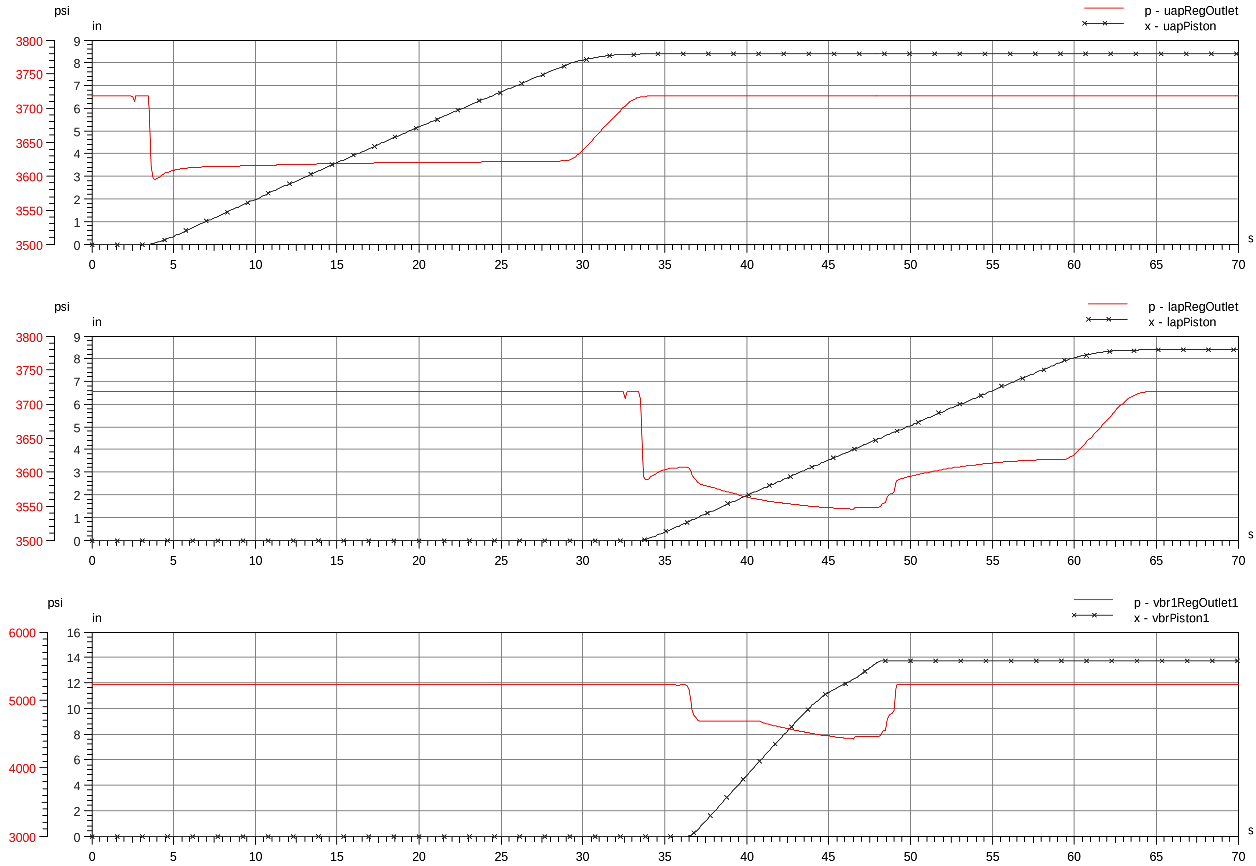


Figure 25) Pressure trends and actuator positions for Case 1-4

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR actuator position	in

When operating one annular preventer followed by a second annular preventer and a VBR in parallel, the LMRP accumulator oil volume drops to a minimum of 67.5 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 5270 psi (3052 psi + static head).

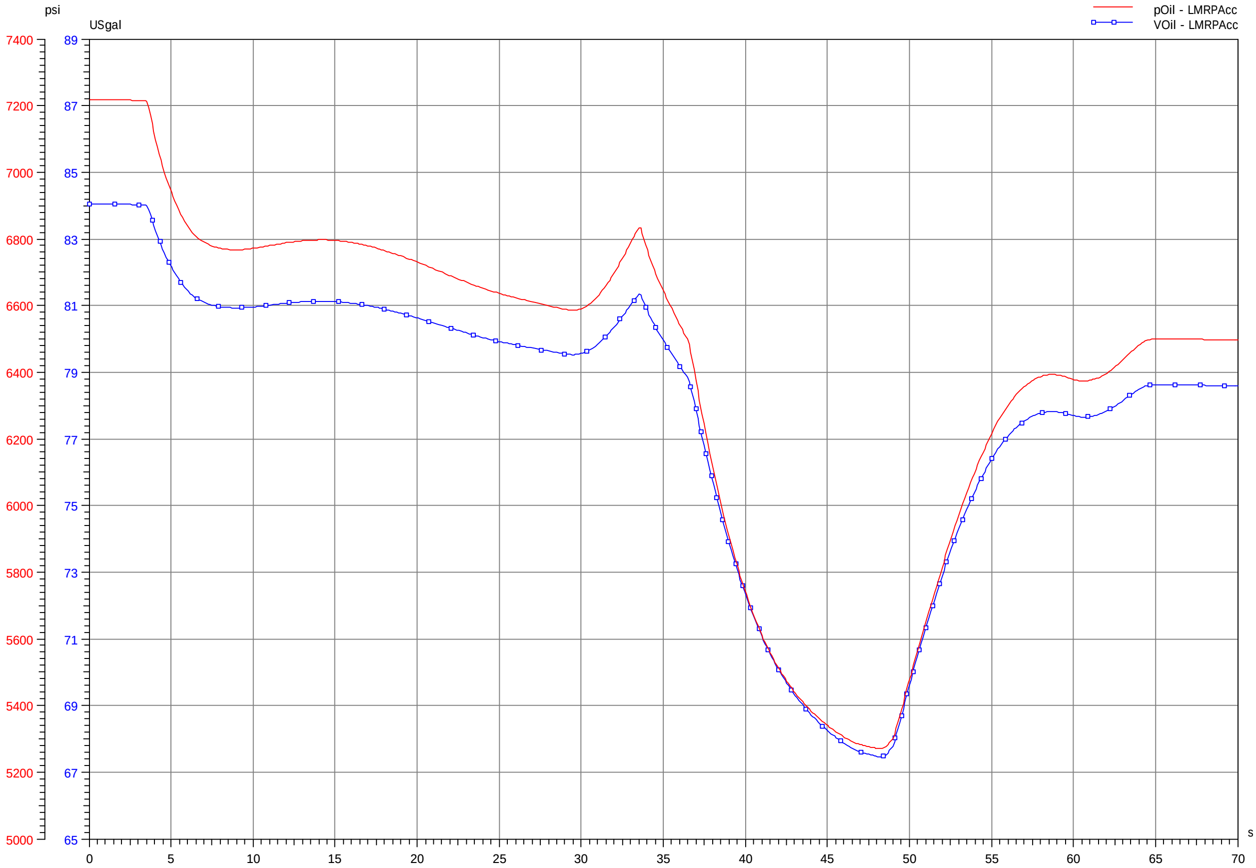


Figure 26) LMRP accumulator pressure and oil volume – Case 1-4

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 27) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while opening one annular preventer followed by a second annular preventer and a VBR in parallel. As can be seen, the pressure drops below 4200 psi and all three pumps starts. The first pump will start at 22 seconds, the second pump at 39 seconds and the last pump at 45 seconds.

Each pump has a flow rate of 25 USgal/min each and together they supply 75 USgal/min to the system.

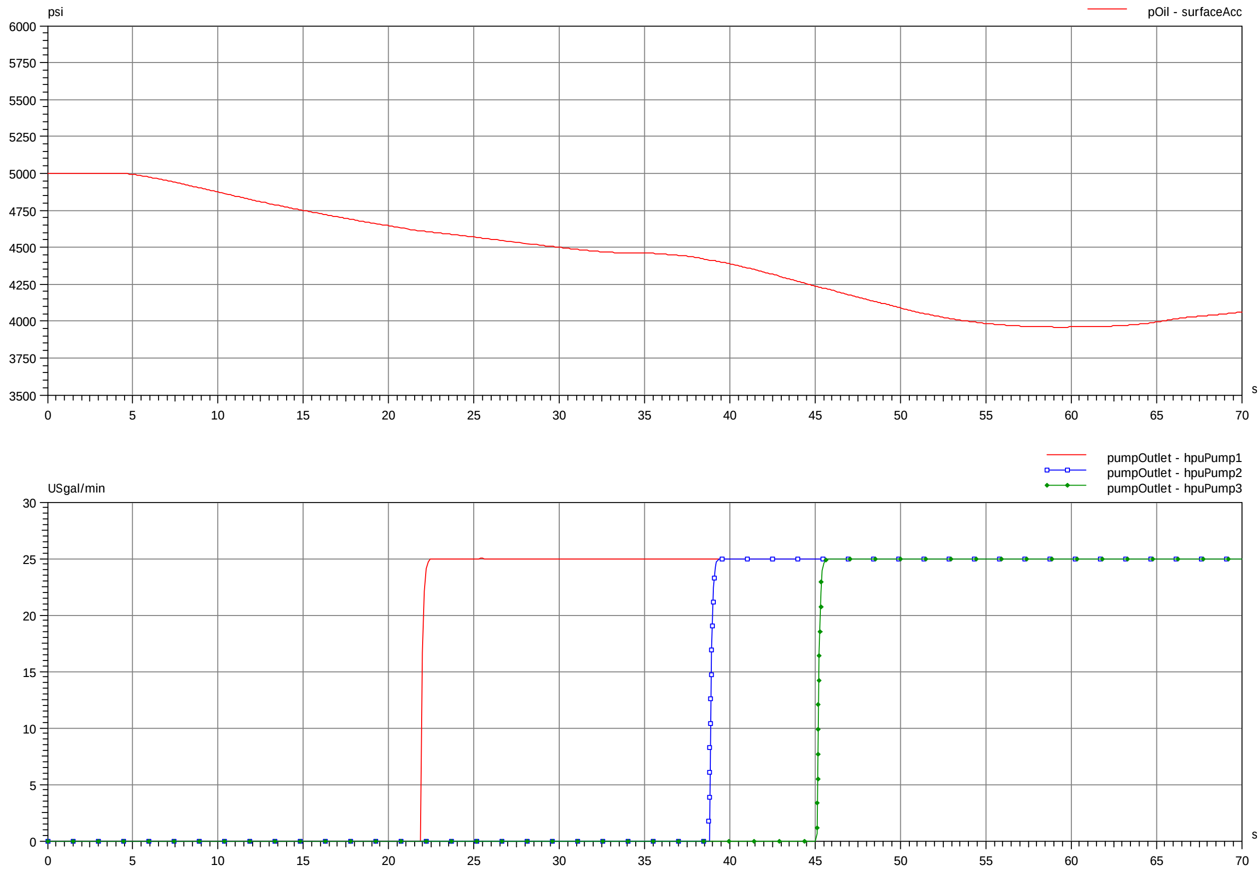


Figure 27) Surface accumulator pressure and pump flows – Case 1-4

Legend:	Description	Unit
pOil - surfaceAcc	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.1.5 Case 1-5: Closing UAP followed by LAP and two VBR's in parallel

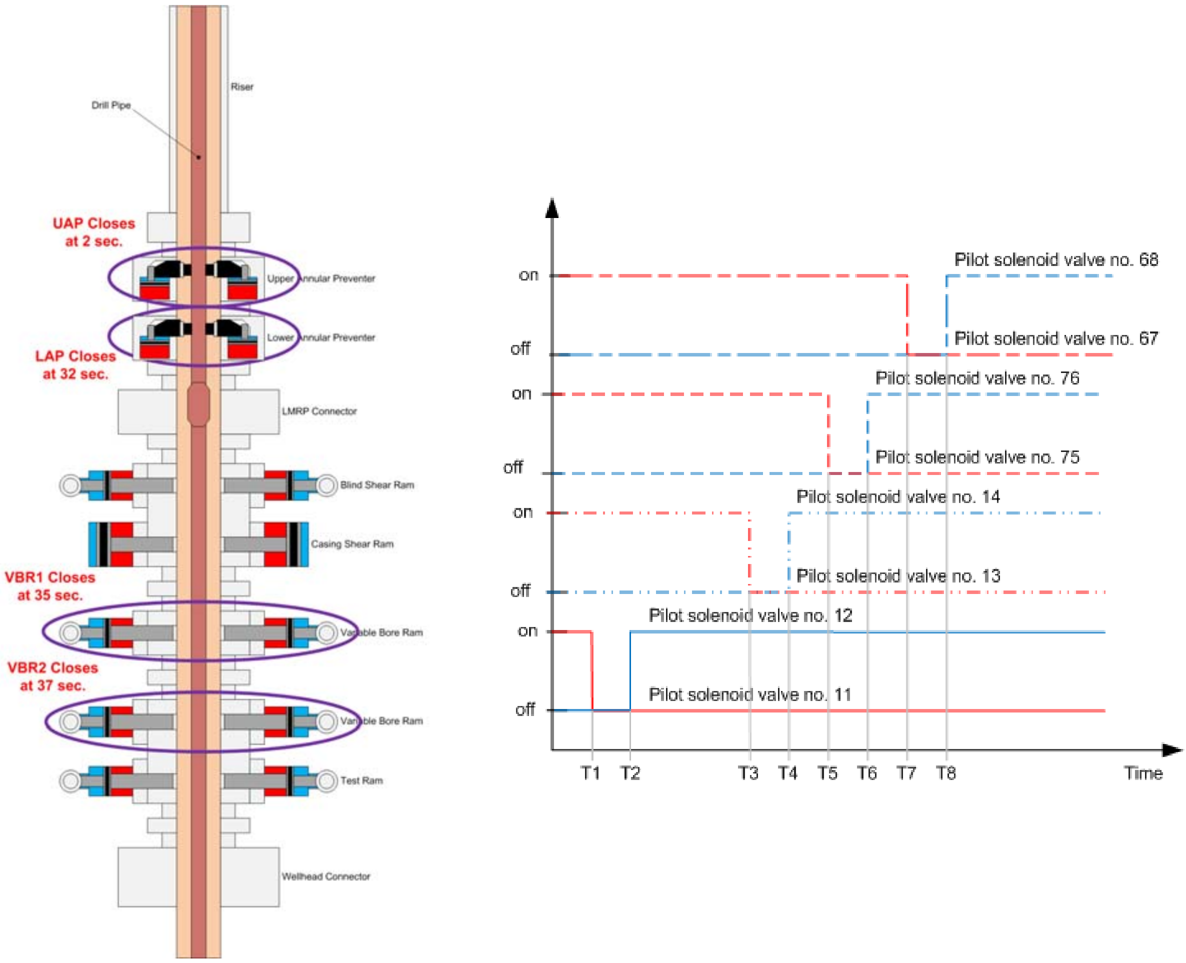


Figure 28) Valve Operation Scheme for Case 1-5

Figure 28) shows the operation of the pilot solenoid valves in the control pod for this case. The time sequence is as follows:

Ident.	Time [sec]	Action
T1	1	Pilot solenoid valve 11 is de-energized to ventilate UAP open line
T2	2	Pilot solenoid valve 12 is energized to pressurize UAP close line
T3	31	Pilot solenoid valve 13 is de-energized to ventilate LAP open line
T4	32	Pilot solenoid valve 14 is energized to pressurize LAP close line
T5	34	Pilot solenoid valve 75 is de-energized to ventilate VBR1 open line
T6	35	Pilot solenoid valve 76 is energized to pressurize VBR1 close line
T7	36	Pilot solenoid valve 67 is de-energized to ventilate VBR2 open line
T8	37	Pilot solenoid valve 68 is energized to pressurize VBR2 close line

Figure 29) shows the pressure trends and actuator positions for the two annular preventers and two VBR's. The first annular preventer is "fired" to open at 2 seconds, the second annular preventer at 32 seconds, the first VBR at 37 seconds and the second VBR at 47 seconds. This opening sequence gives parallel operation between the last annular preventer and the VBR's.

All BOP valves operate as expected and there is no sign of reduced system capacity from the valve behaviour.

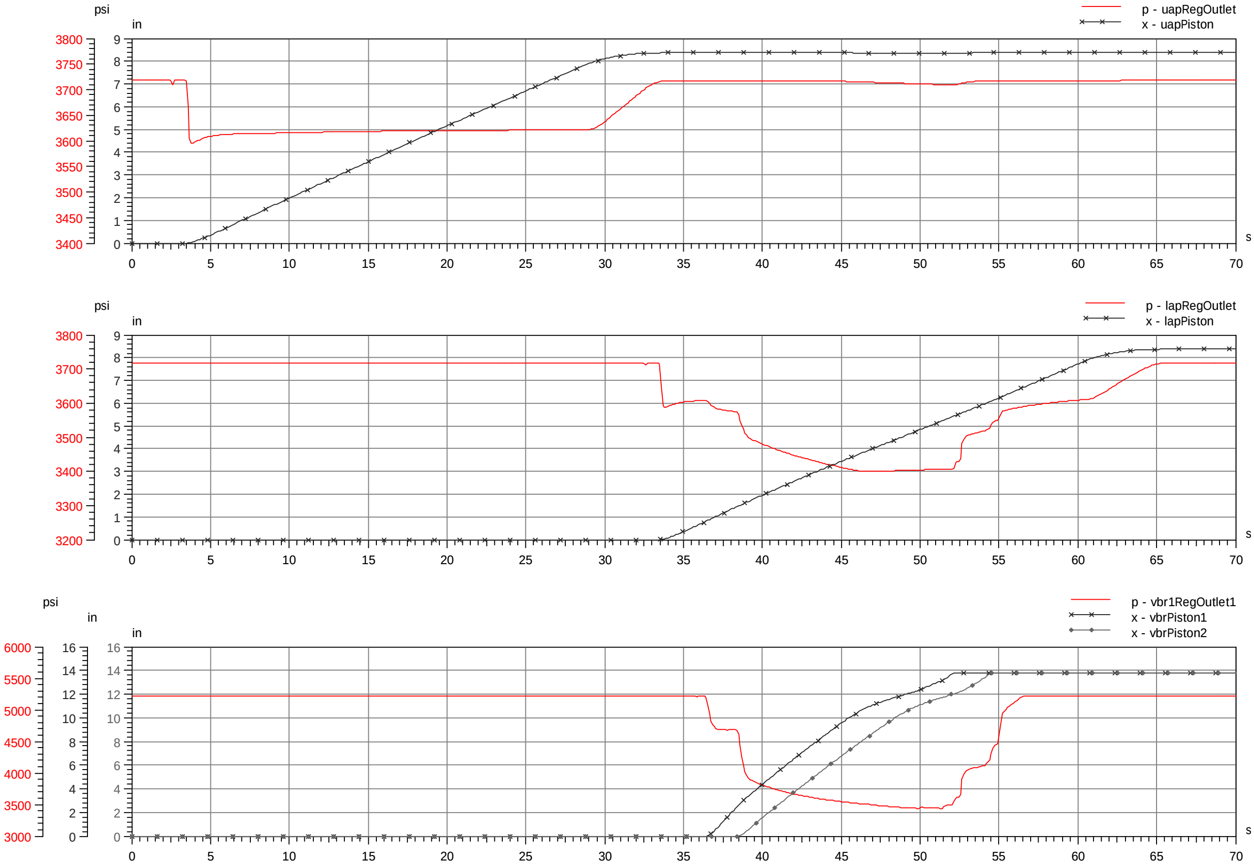


Figure 29)   Pressure trends and actuator positions for Case 1-5

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR1 actuator position	in
x – vbrPiston2	VBR2 actuator position	in

When operating one annular preventer followed by a second annular preventer and two VBR's in parallel, the LMRP accumulator oil volume drops to a minimum of 60.5 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 4700 psi (2482 psi + static head).

The system pressure drops below normal operating pressure for the VBR's (3000 psi + static head) but remains above recommended operating pressure for the annular preventers (1500 psi + static head).

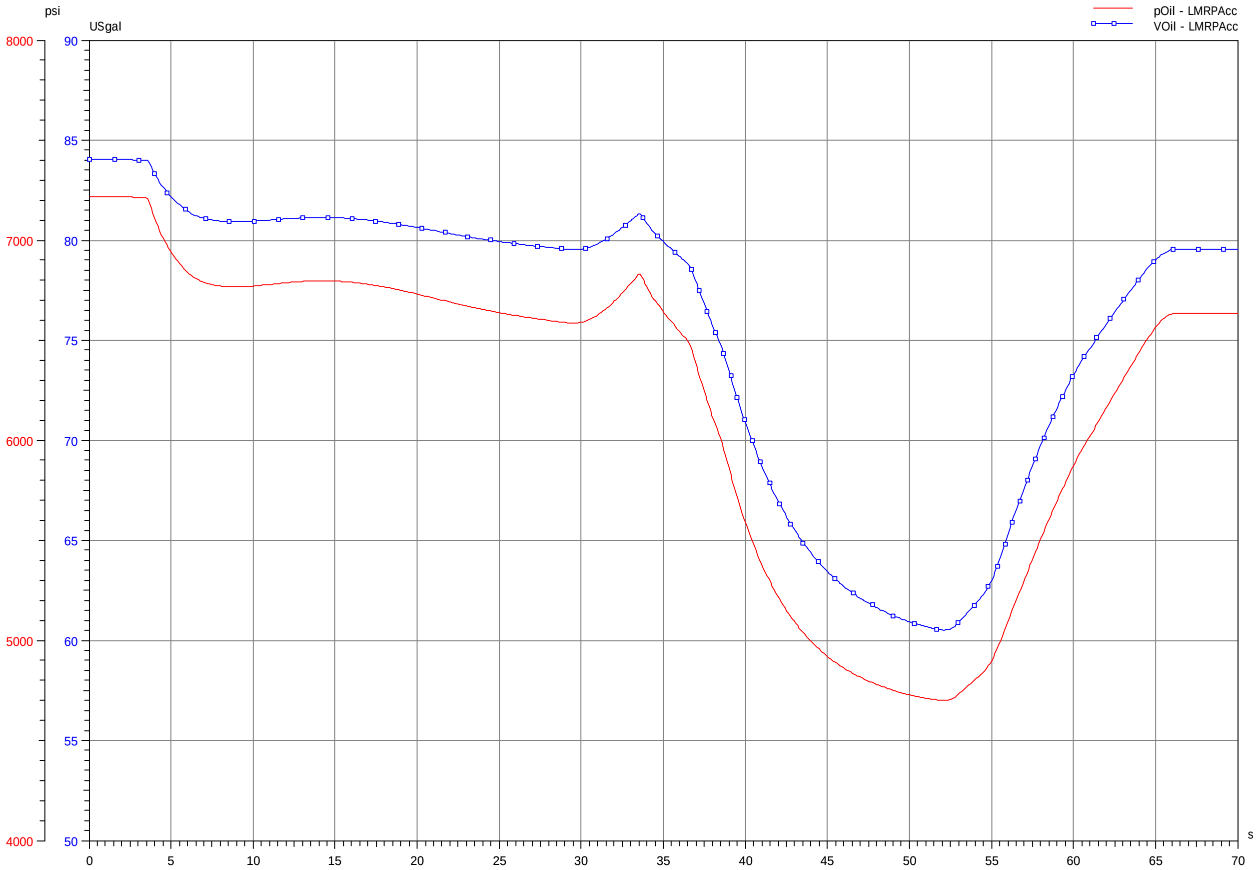


Figure 30) LMRP accumulator pressure and oil volume – Case 1-5

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 31) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while opening one annular preventer followed by a second annular preventer and a VBR in parallel. As can be seen, the pressure drops below 4200 psi and all three pumps starts. The first pump will start at 22 seconds, the second pump at 39 seconds and the last pump at 44 seconds.

The pumps have a flow rate of 25 USgal/min each and together they supply 75 USgal/min to the system.

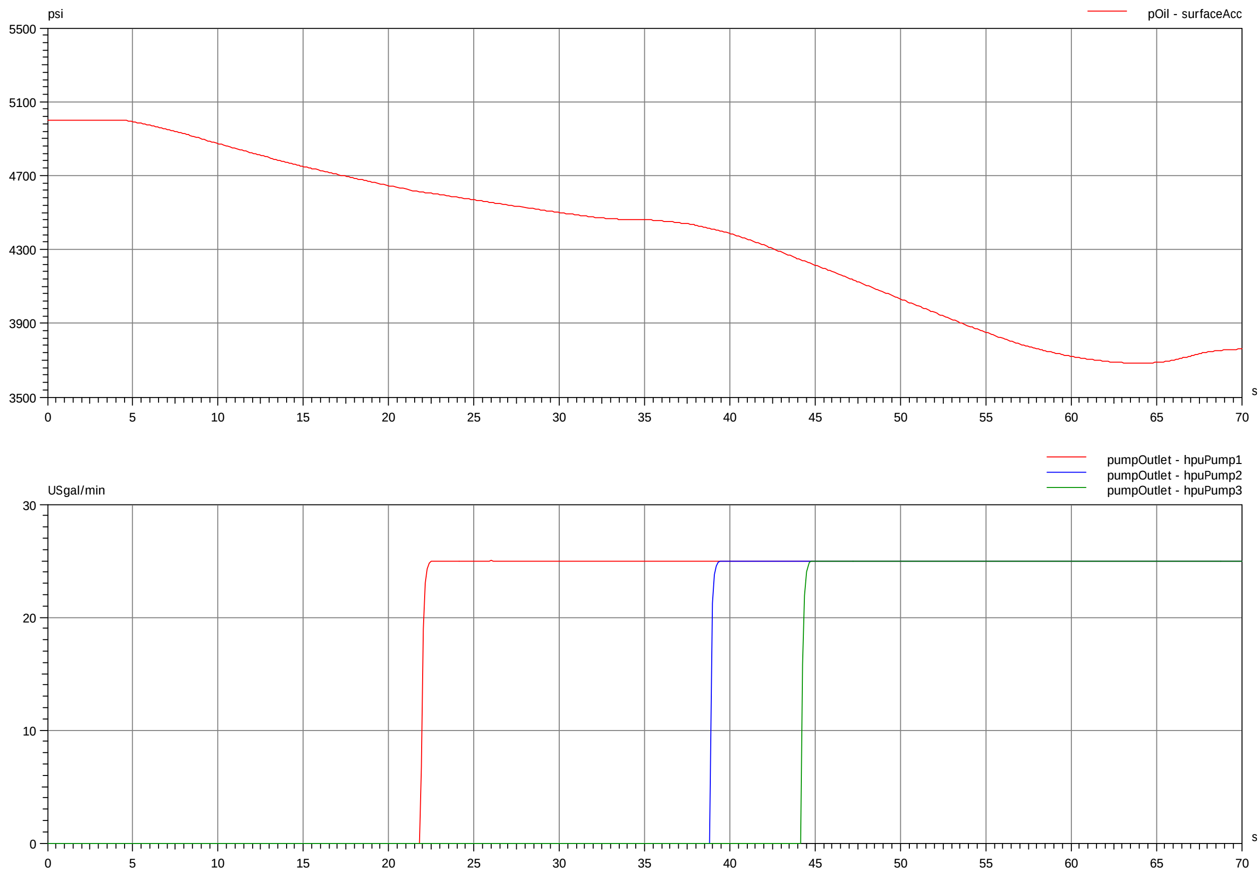


Figure 31) Surface accumulator pressure and pump flows – Case 1-5

Legend:	Description	Unit
pOil - surfaceAcc	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.1.6 Case 1-6: Closing UAP, LAP and one VBR in parallel

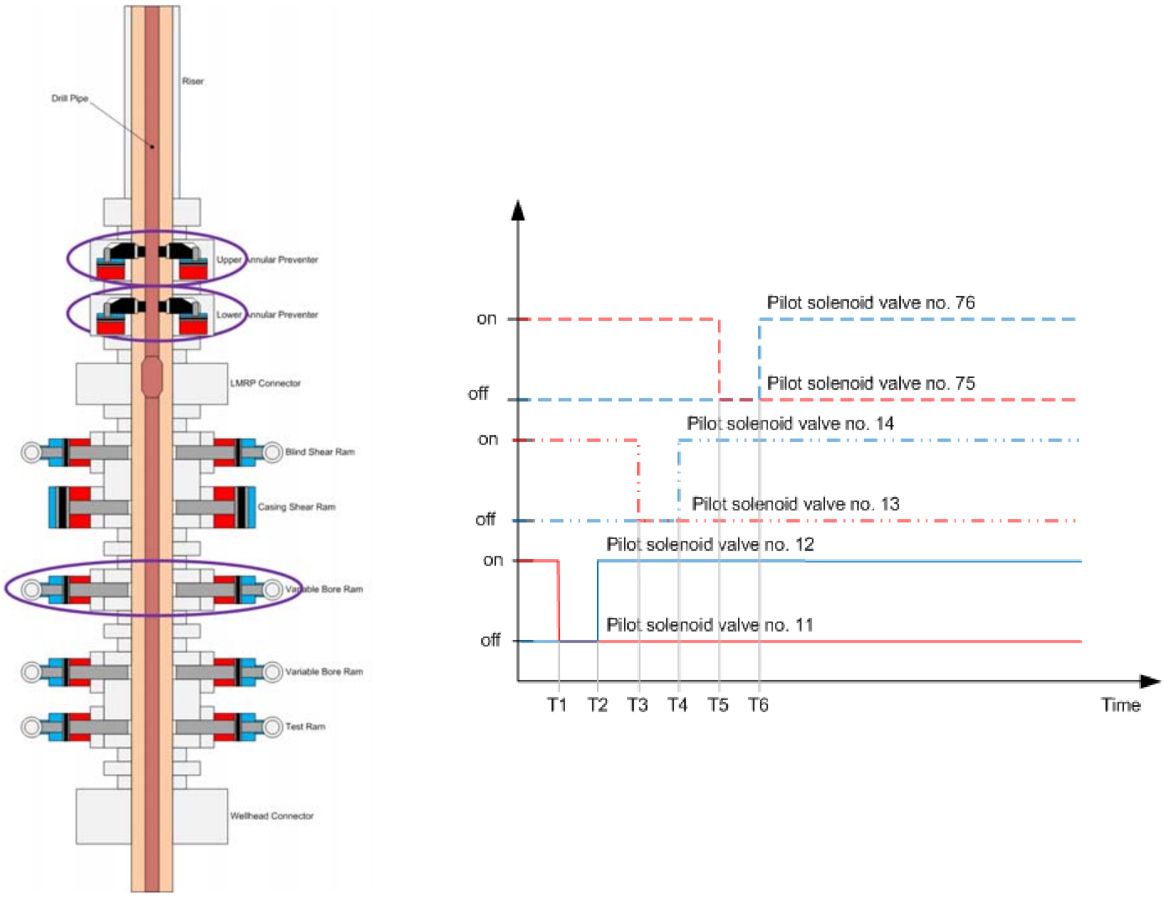


Figure 32) Valve Operation Scheme for Case 1-6

Figure 32) shows the operation of the pilot solenoid valves in the control pod for this case. The time sequence is as follows:

Ident.	Time [sec]	Action
T1	1	Pilot solenoid valve 11 is de-energized to ventilate UAP open line
T2	2	Pilot solenoid valve 12 is energized to pressurize UAP close line
T3	3	Pilot solenoid valve 13 is de-energized to ventilate LAP open line
T4	4	Pilot solenoid valve 14 is energized to pressurize LAP close line
T5	5	Pilot solenoid valve 75 is de-energized to ventilate VBR1 open line
T6	6	Pilot solenoid valve 76 is energized to pressurize VBR1 close line

Figure 33) shows the pressure trends and actuator positions for the two annular preventers and two VBR's. The first annular preventer is "fired" to open at 2 seconds, the second annular at 4 seconds and the VBR at 6 seconds. This gives a parallel operation of all three actuators.

All BOP valves operate as expected and there is no sign of reduced system capacity in the valve behaviour.

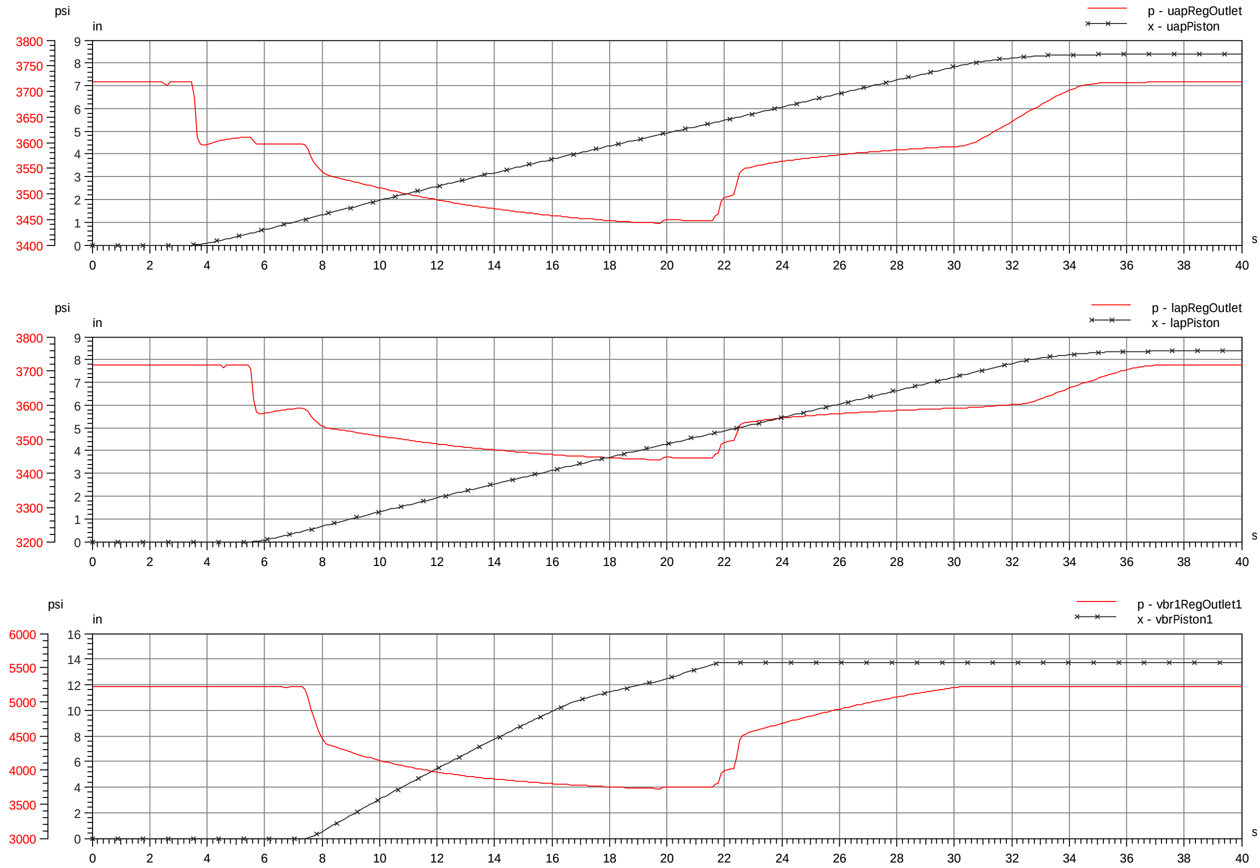


Figure 33) Pressure trends and actuator positions for Case 1-6

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR1 actuator position	in
x – vbrPiston2	VBR2 actuator position	in

When operating the two annular preventers and the VBR in parallel, the LMRP accumulator oil volume drops to a minimum of 63.7 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 4946 psi (2728 psi + static head).

The system pressure drops below normal operating pressure for the VBR's (3000 psi + static head) but remains above recommended operating pressure for the annular preventers (1500 psi + static head).

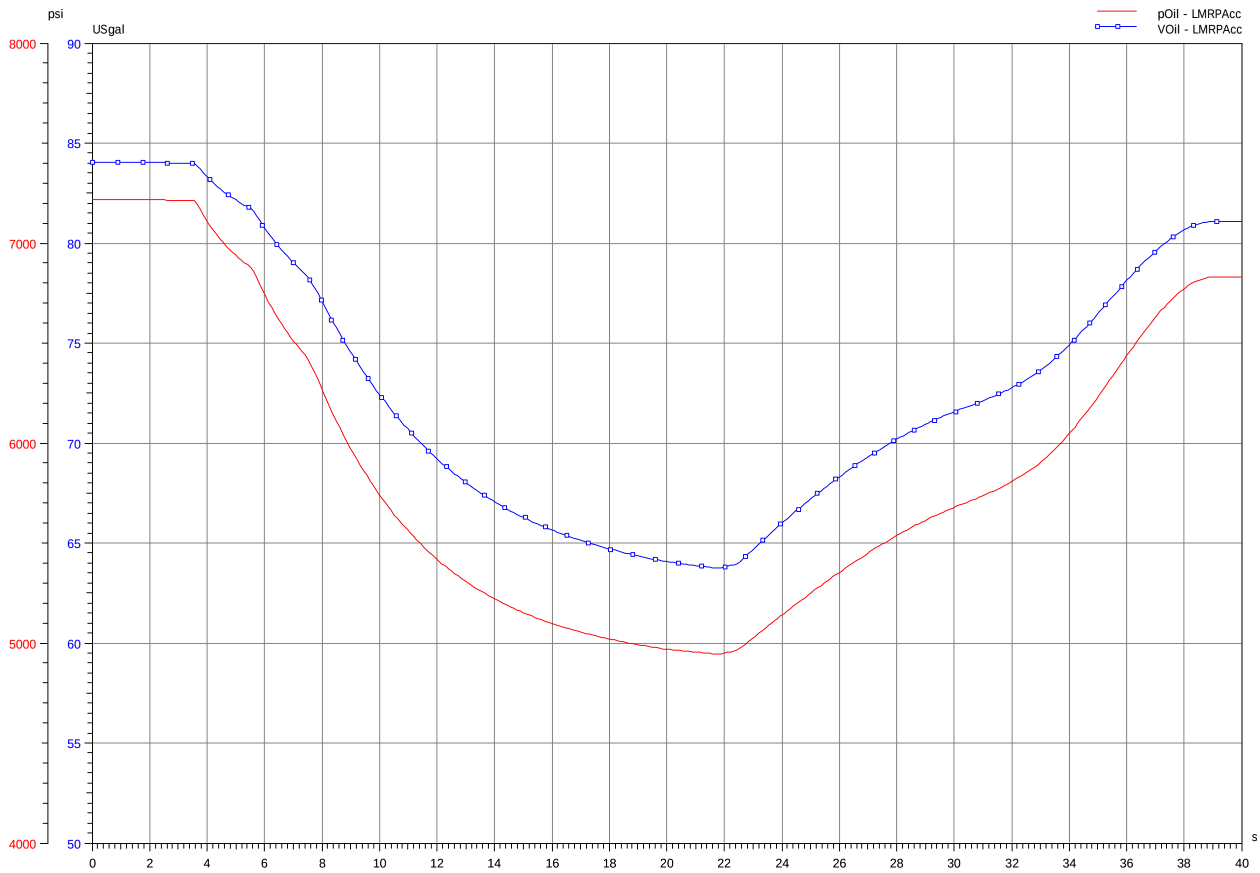


Figure 34) LMRP accumulator pressure and oil volume – Case 1-6

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 35) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while closing two annular preventers and a VBR in parallel. As can be seen, the pressure drops below 4200 psi and all three pumps starts. The first pump will start at 13 seconds, the second pump at 17 seconds and the last pump after some 21 seconds.

The pumps have a flow rate of 25 USgal/min each and together they supply 75 USgal/min to the system.

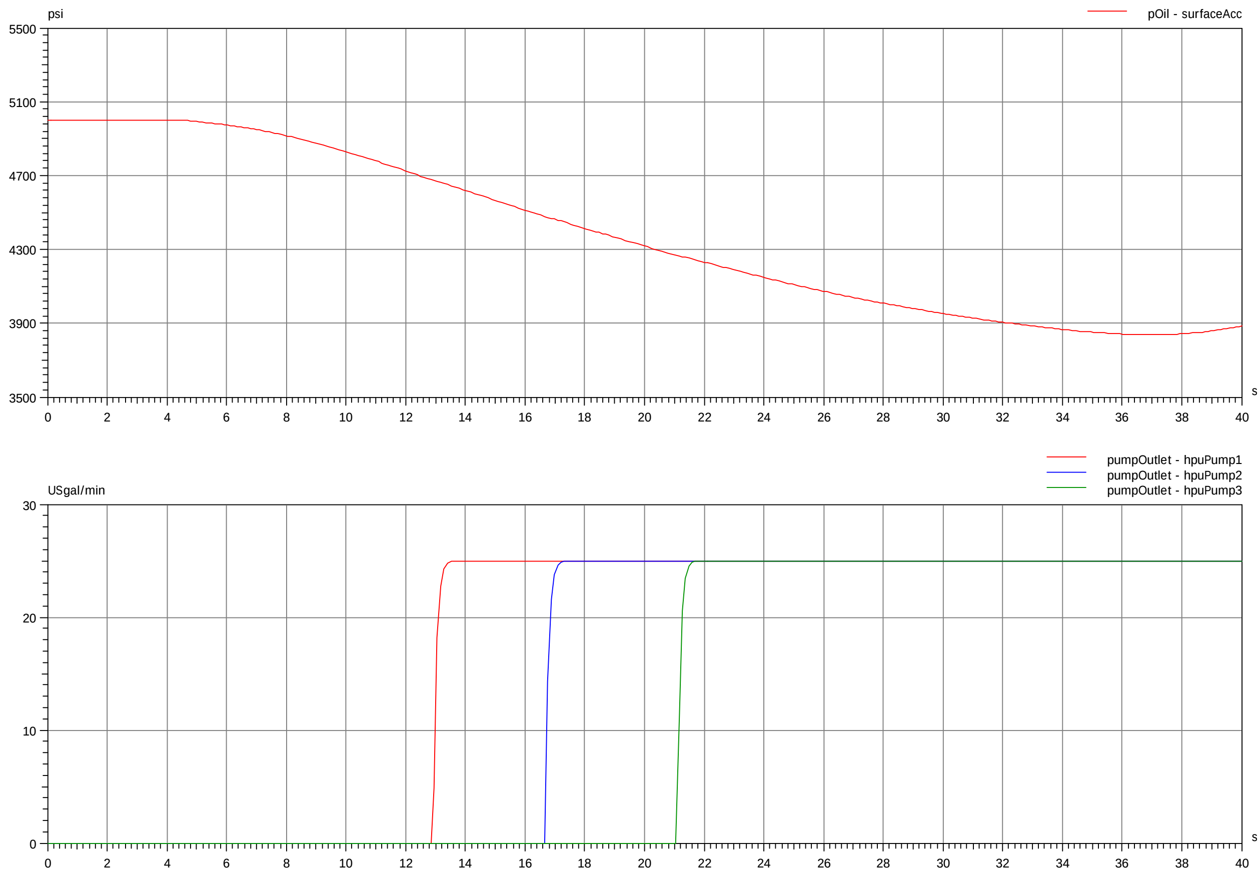


Figure 35) Surface accumulator pressure and pump flows – Case 1-6

Legend:	Description	Unit
pOil - surface	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.1.7 Case 1-7: Closing UAP, LAP and two VBR's in parallel

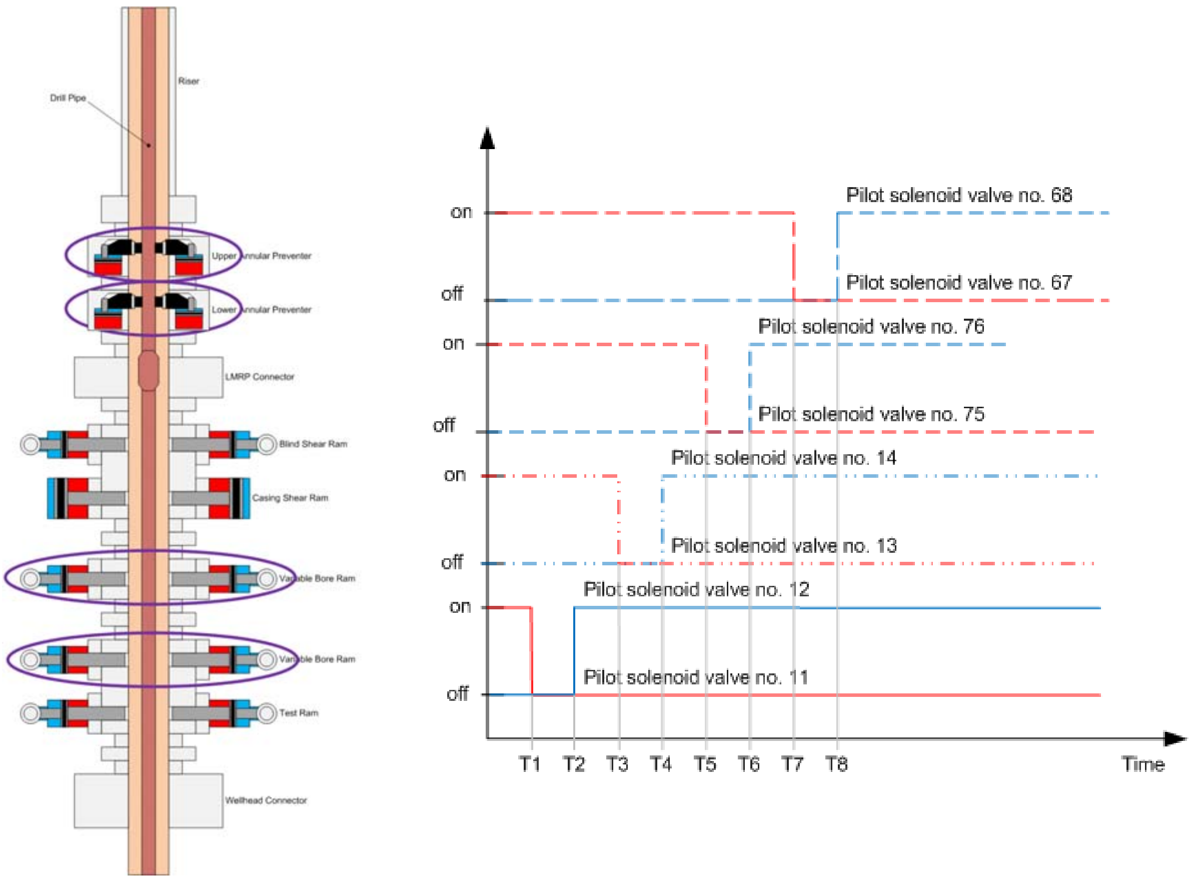


Figure 36) Valve Operation Scheme for Case 1-7

Figure 36) shows the operation of the pilot solenoid valves in the control pod for this case. The time sequence is as follows:

Ident.	Time [sec]	Action
T1	1	Pilot solenoid valve 11 is de-energized to ventilate UAP open line
T2	2	Pilot solenoid valve 12 is energized to pressurize UAP close line
T3	3	Pilot solenoid valve 13 is de-energized to ventilate LAP open line
T4	4	Pilot solenoid valve 14 is energized to pressurize LAP close line
T5	5	Pilot solenoid valve 75 is de-energized to ventilate VBR1 open line
T6	6	Pilot solenoid valve 76 is energized to pressurize VBR1 close line
T7	7	Pilot solenoid valve 67 is de-energized to ventilate VBR2 open line
T8	8	Pilot solenoid valve 68 is energized to pressurize VBR2 close line

Figure 37) shows the pressure trends and actuator positions for the two annular preventers and two VBR's. The first annular preventer is "fired" to open at 2 seconds, the second annular at 4 seconds, the first VBR at 6 seconds and the second VBR at 8 seconds. This gives a parallel operation of all four actuators.

As can be seen from the opening times, all actuators needs significant longer time to complete their strokes compared to previous case.

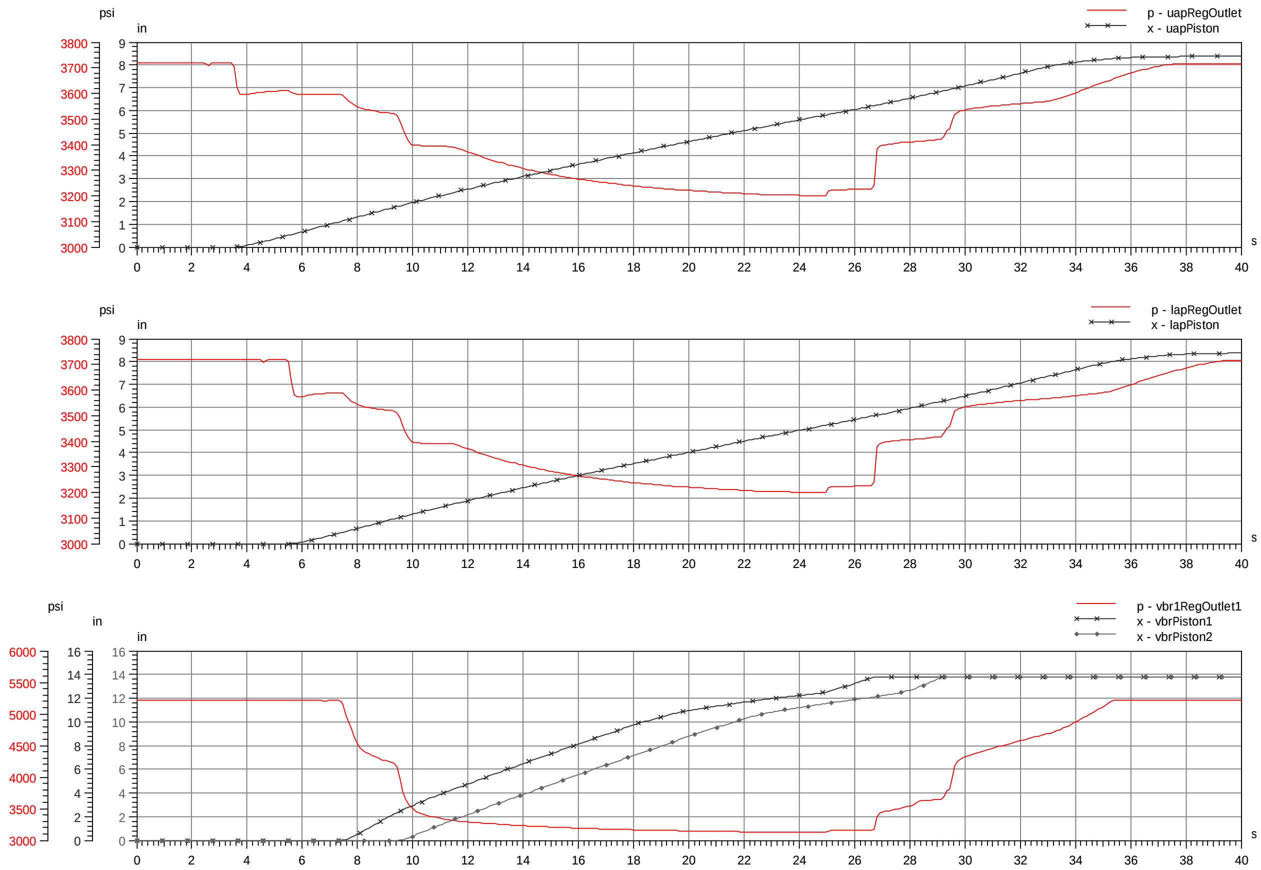


Figure 37) Pressure trends and actuator positions for Case 1-7

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR1 actuator position	in
x – vbrPiston2	VBR2 actuator position	in

When operating the two annular preventers and two VBR's in parallel, the LMRP accumulator oil volume drops to a minimum of 57.8 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 4580 psi (2362 psi + static head).

The system pressure drops below normal operating pressure for the VBR's (3000 psi + static head) but remains above recommended operating pressure for the annular preventers (1500 psi + static head).

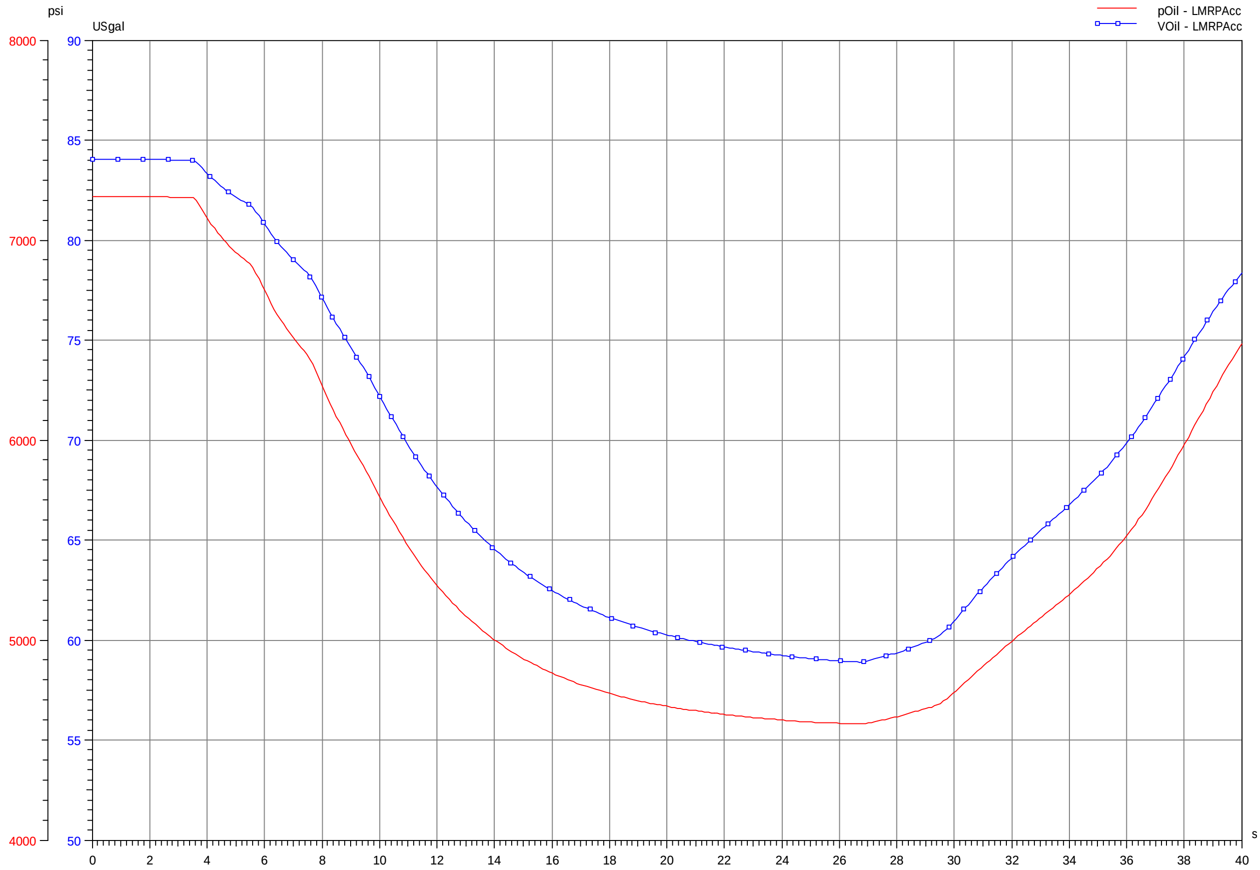


Figure 38) LMRP accumulator pressure and oil volume – Case 1-7

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 39) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while closing two annular preventers and a VBR in parallel. As can be seen, the pressure drops below 4200 psi and all three pumps starts. The first pump will start at 13 seconds, the second pump at 16 seconds and the last pump at 20 seconds.

The pumps have a flow rate of 25 USgal/min each and together they supply 75 USgal/min to the system.

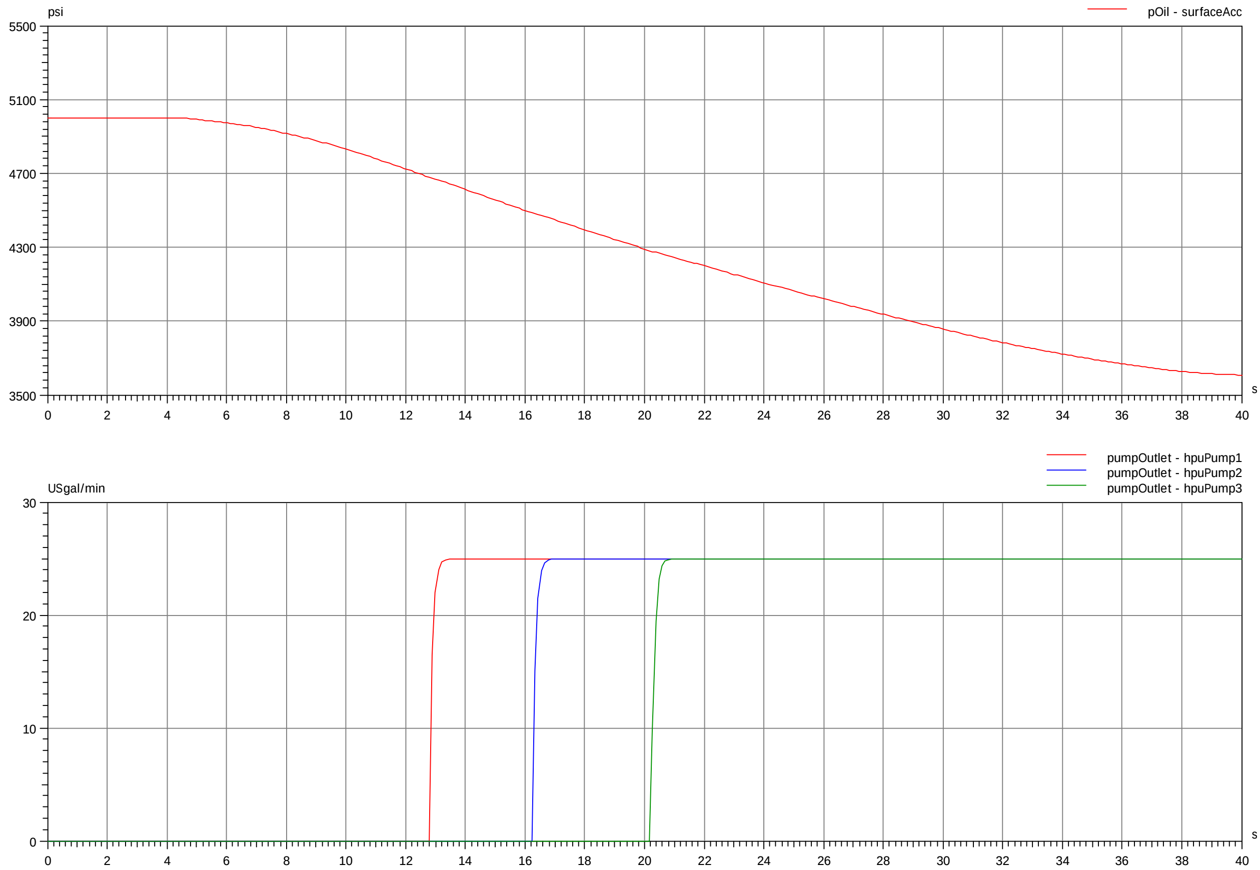


Figure 39) Surface accumulator pressure and pump flows – Case 1-7

Legend:	Description	Unit
pOil - surfaceAcc	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.2 Scenario 2: Parallel operations with reduced LMRP acc. capacity

The scope of this scenario is to verify if the BOP hydraulic system has capacity to perform parallel operations with reduced accumulator capacity.

The scenario of parallel operations has been divided in to 5 cases:

Case 2-1: Closing one annular preventer followed by a second annular preventer

Case 2-2: Closing one annular preventer followed by the second annular preventer and one VBR in parallel

Case 2-3: Closing one annular preventer followed by the second annular preventer and two VBR’s in parallel

Case 2-4: Closing two annular preventers and one VBR in parallel.

Case 2-5: Closing two annular preventers and two VBR’s in parallel.

All five cases are simulated with a) reduced pre-charge pressure (3000 psi) and b) reduced accumulator volume. I. e. one out of four accumulators has lost the pre-filled gas.

5.2.1 Case 2-1: Closing UAP and LAP in series

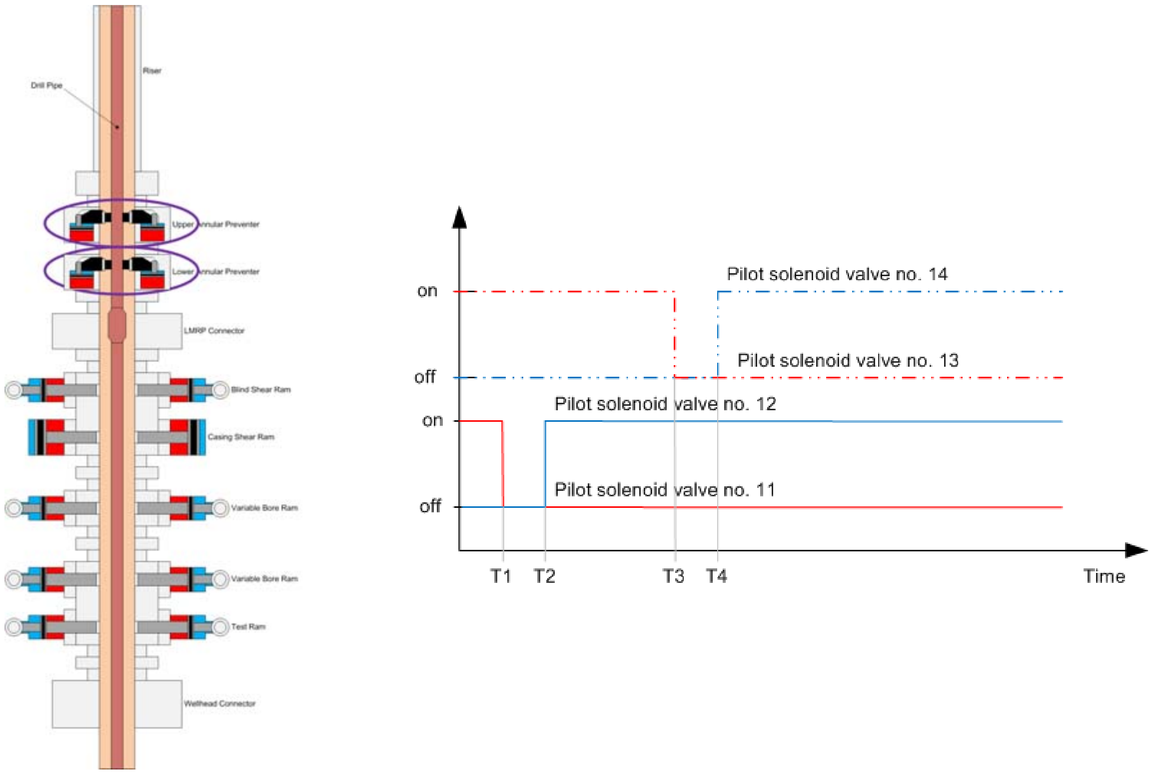


Figure 40) Valve Operation Scheme for Case 2-1

Figure 40) shows the operation of the pilot solenoid valves in the control pod for this case. The time sequence is as follows:

Ident.	Time [sec]	Action
T1	1	Pilot solenoid valve 11 is de-energized to ventilate UAP open line
T2	2	Pilot solenoid valve 12 is energized to pressurize UAP close line
T3	31	Pilot solenoid valve 13 is de-energized to ventilate LAP open line
T4	32	Pilot solenoid valve 14 is energized to pressurize LAP close line

Note: This case is comparable with Case 1-3

5.2.1.1 Case 2-1a: With 3000 psi pre-charge pressure in LMRP accumulators

Figure 41) shows the pressure trends and actuator positions for the two annular preventers. The first annular preventer is “fired” to close at 2 seconds and the second at 32 seconds.

There is no difference in the actuator performance compared to the simulations performed for the system with pre-charge pressure according to specifications.

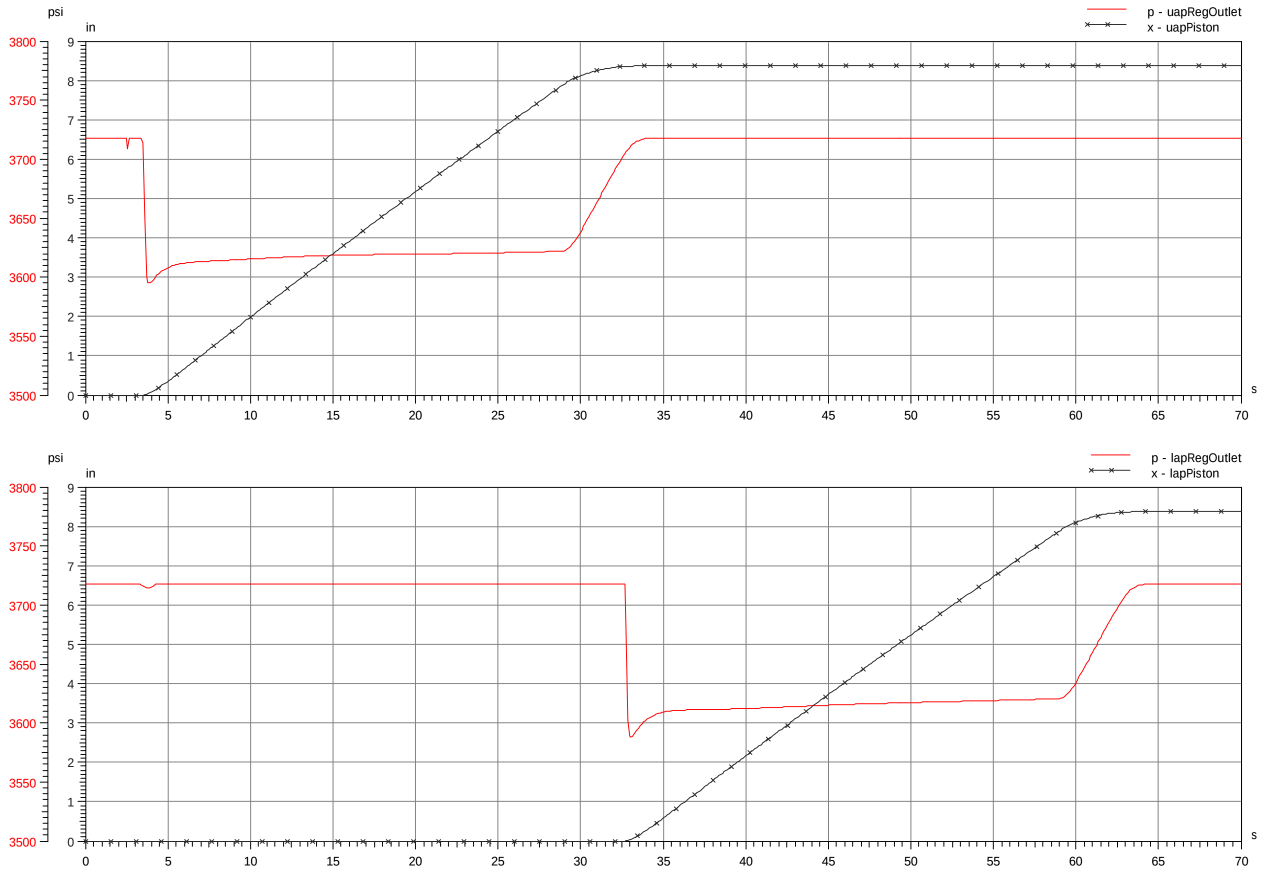


Figure 41) Pressure trends and actuator positions for Case 2-1a

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in

The LMRP accumulator oil volume is initially 115.7 USgal which is 31.7 USgal more than for the system pre-charged according to specifications.

When operating the two annular preventers as in series, the LMRP accumulator oil volume drops to a minimum of 110.2 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 6310 psi (4092 psi + static head).

Minimum pressure is 10 psi lower than for the same system with pre-charge pressure according to specifications.

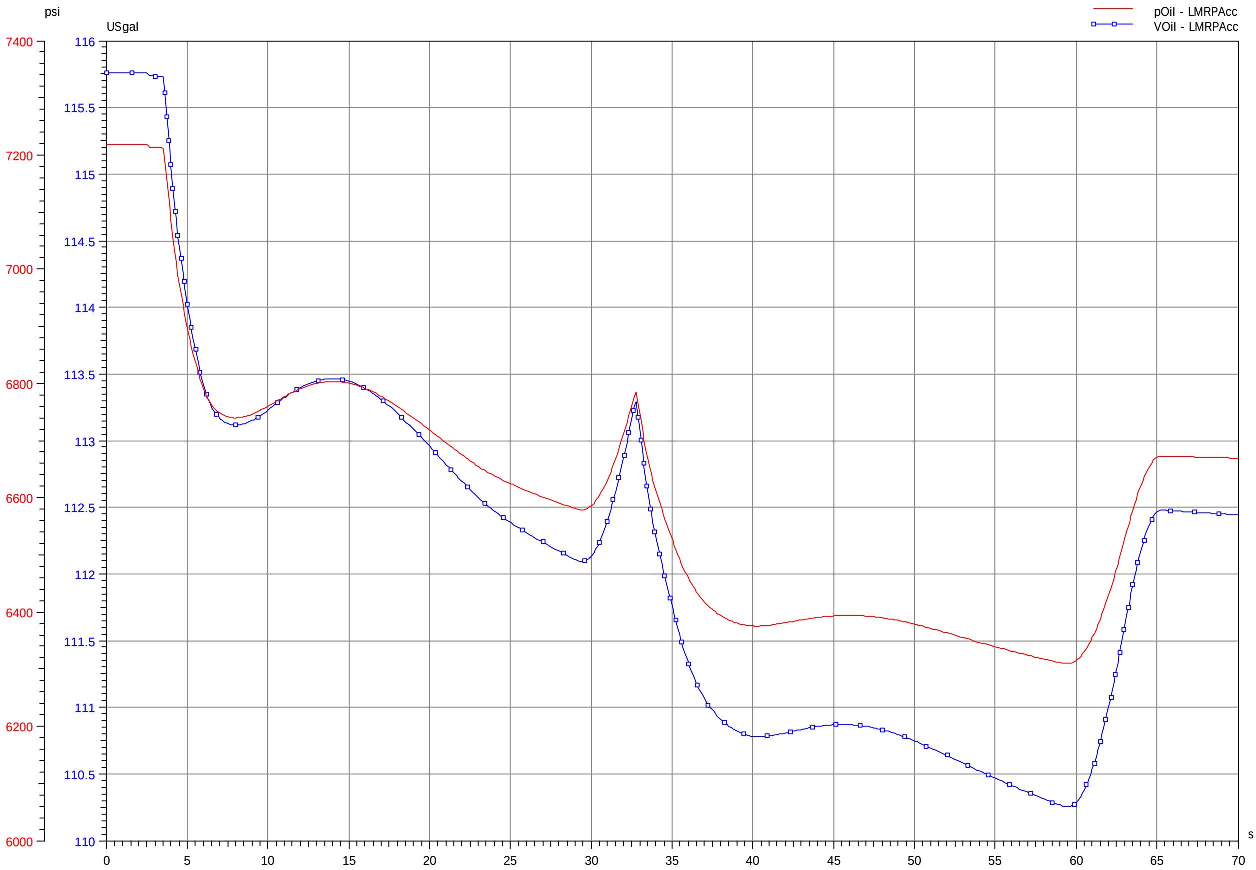


Figure 42) LMRP accumulator pressure and oil volume – Case 2-1a

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 43) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while operating two annular preventers in series. As can be seen, the first pump starts at 21 seconds and the second pump starts at 38 seconds.

Minimum surface accumulator pressure is 4196 psi.

Each pump has a flow rate of 25 USgal/min each and together they supply 50 USgal/min to the system.

The surface system has similar pressure behaviour as for the system with LMRP accumulators pre-charged according to specifications.

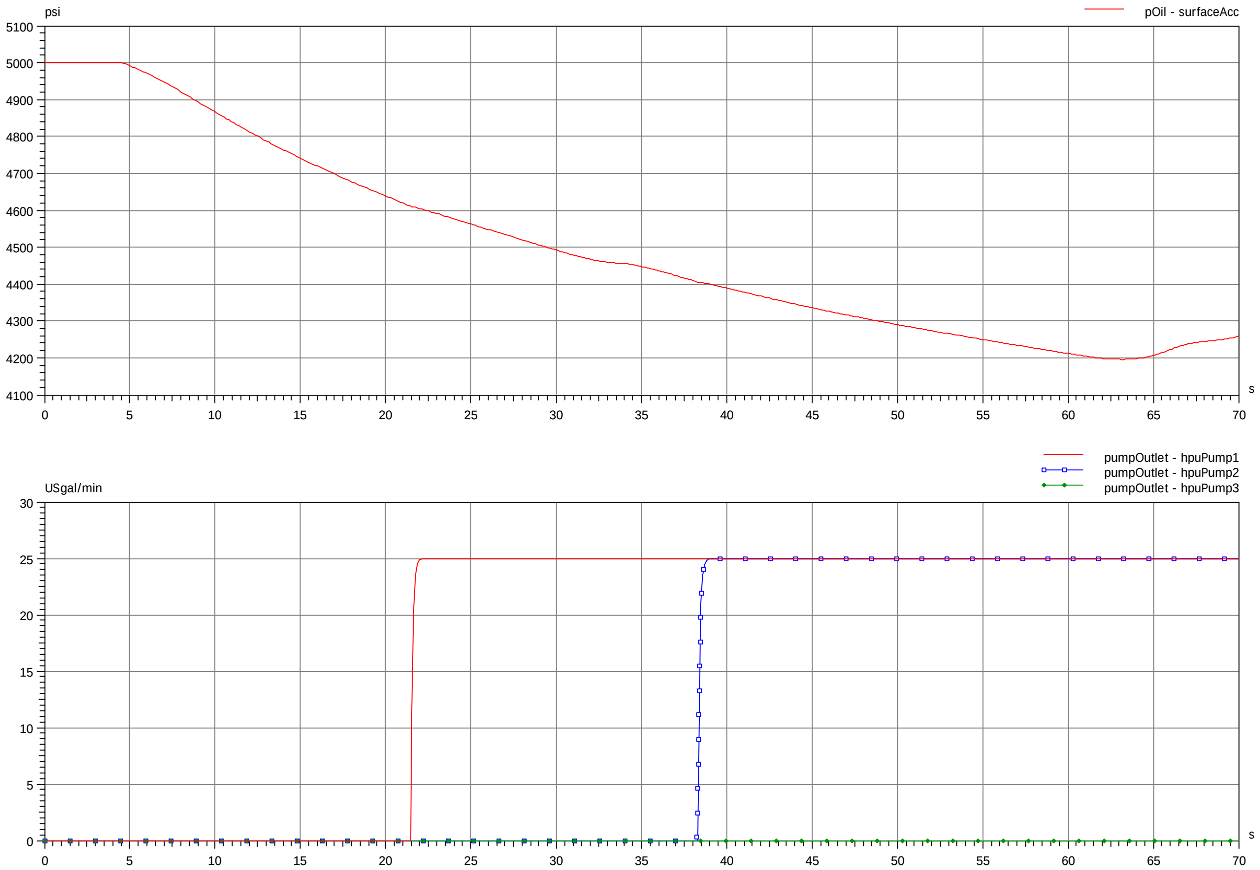


Figure 43) Surface accumulator pressure and pump flows – Case 2-1a

Legend:	Description	Unit
pOil - surfaceAcc	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.2.1.2 Case 2-1b: With three out of four LMRP accumulators available

Figure 44) shows the pressure trends and actuator positions for the two annular preventers. The first annular preventer is “fired” to close at 2 seconds and the second at 32 seconds.

There is no difference in the actuator performance compared to the simulations performed for the system with pre-charge pressure according to specifications.

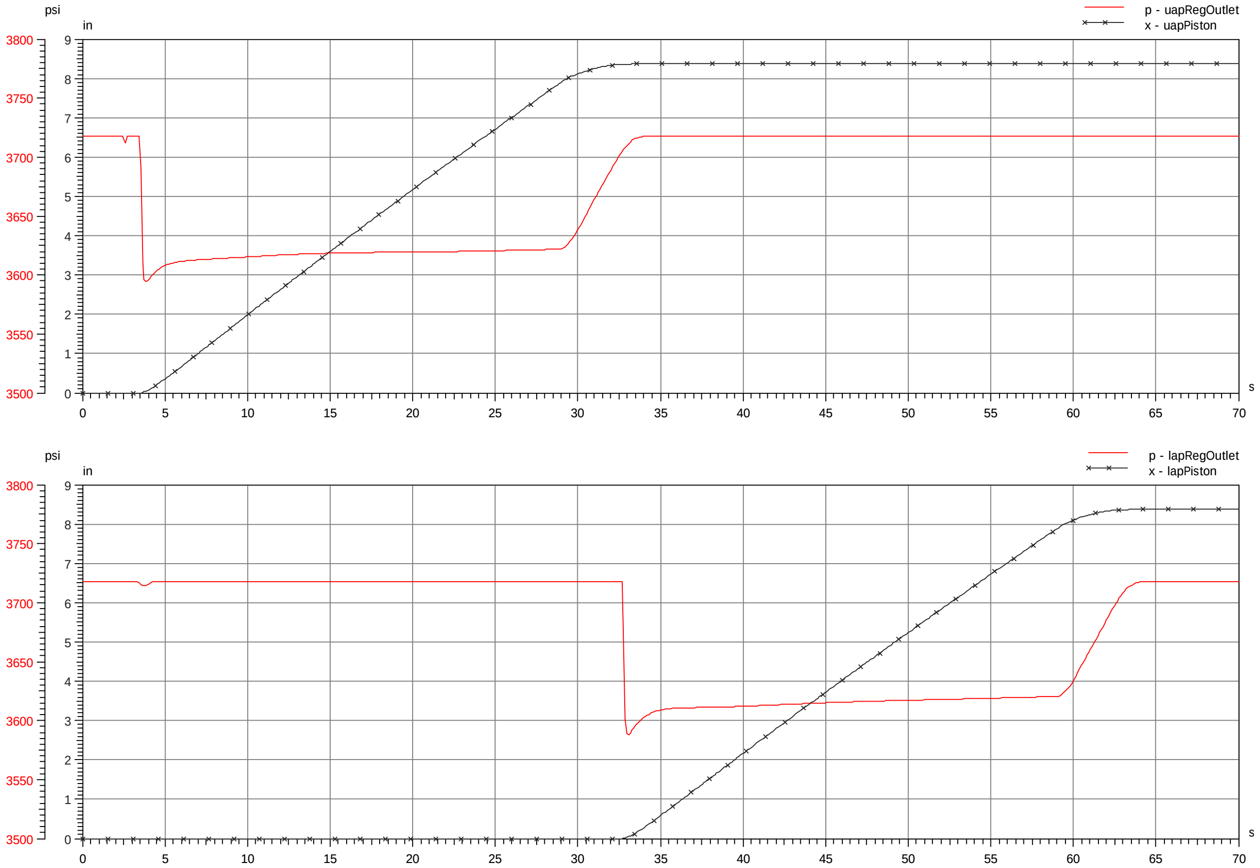


Figure 44) Pressure trends and actuator positions for Case 2-1b

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in

The LMRP accumulator oil volume is initially 63.2 USgal which is 20.8 USgal less than for the same system with all four accumulators available.

When operating the two annular preventers in series, the LMRP accumulator oil volume drops to a minimum of 58.1 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 6306 psi (4098 psi + static head).

Minimum pressure is 4 psi lower than for the same system with all four accumulators available.

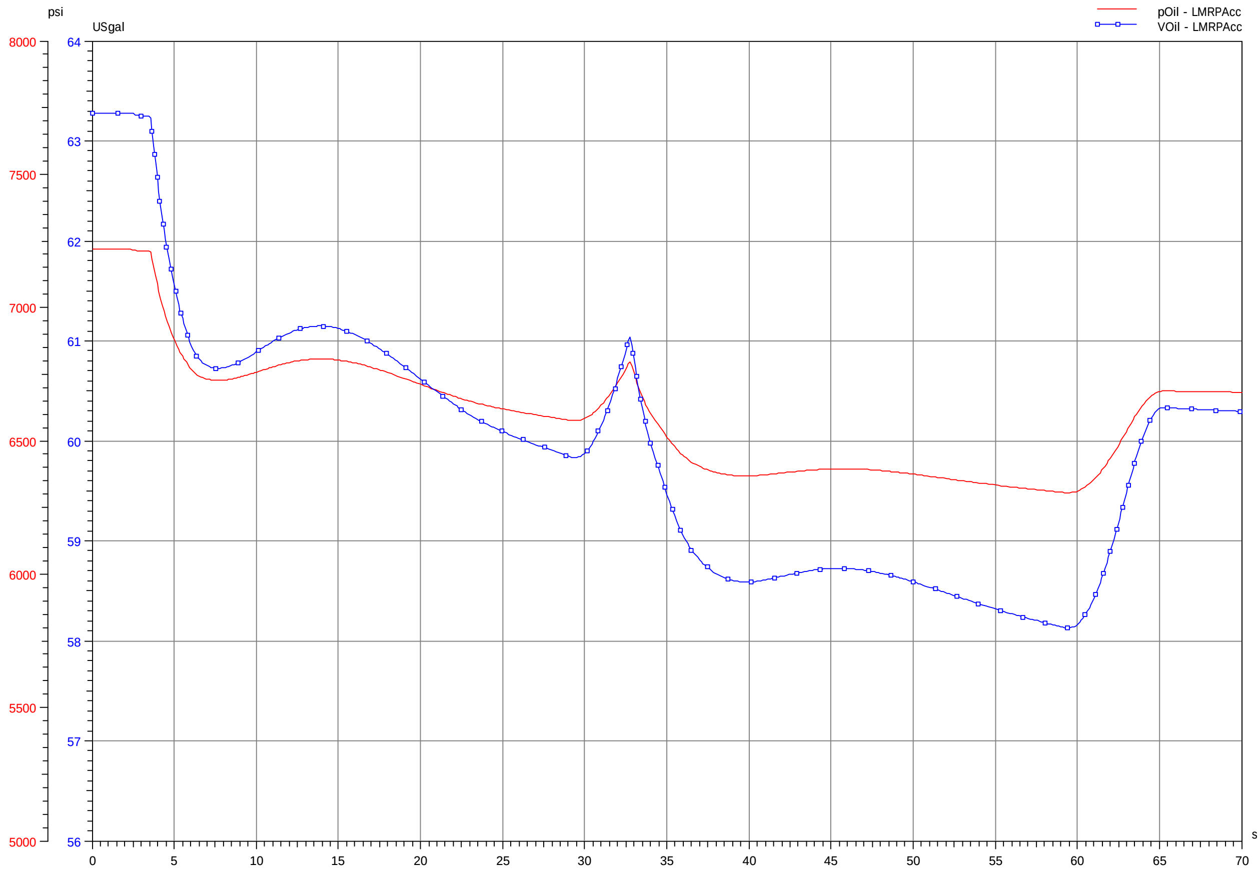


Figure 45) LMRP accumulator pressure and oil volume – Case 2-1b

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 46) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while opening two annular preventers in series. As can be seen, the pressure drops below 4200 psi and all three pumps starts. The first pump will start at 21 seconds, the second pump at 38 seconds and the last pump at 62 seconds.

The surface system has similar pressure behaviour as for the system with LMRP accumulators pre-charged according to specifications.

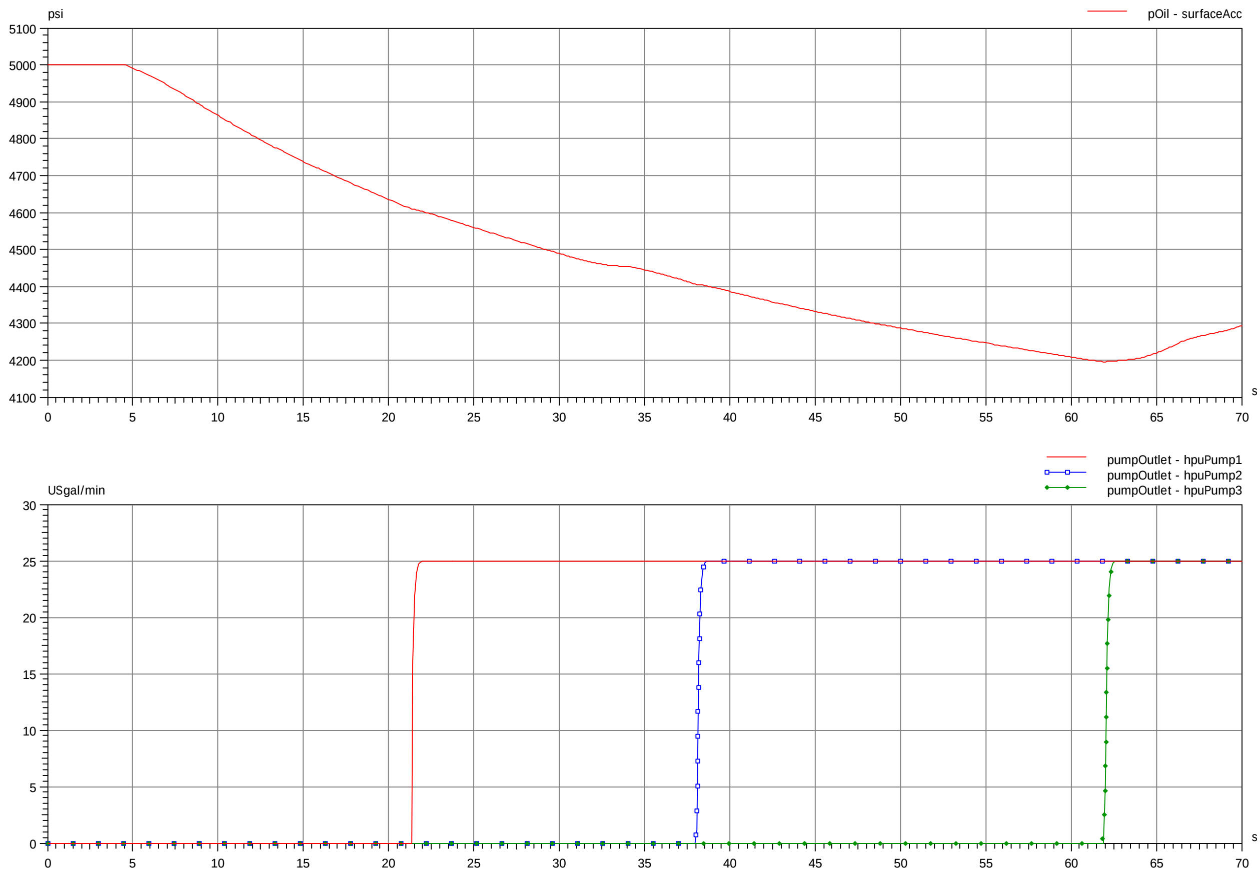


Figure 46) Surface accumulator pressure and pump flows – Case 2-1b

Legend:	Description	Unit
pOil - surfaceAcc	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.2.2 Case 2-2: Closing UAP followed by LAP and one VBR in parallel

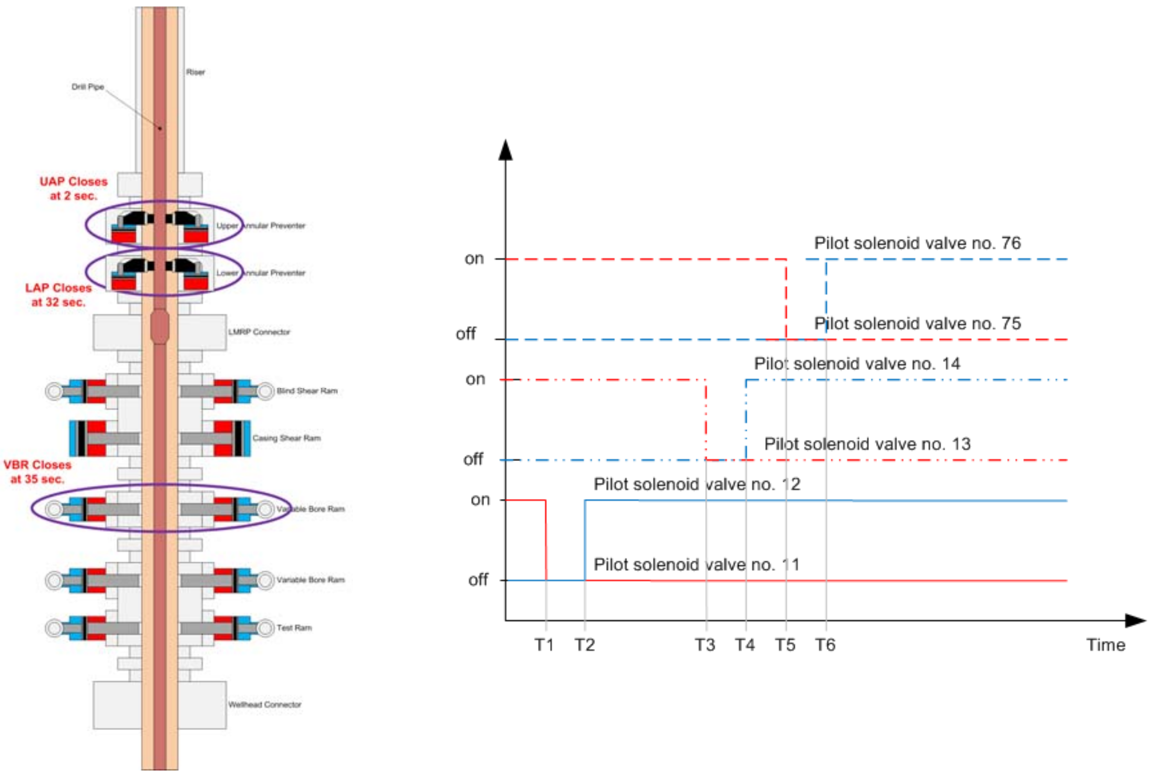


Figure 47) Valve Operation Scheme for Case 2-2

Figure 24) shows the operation of the pilot solenoid valves in the control pod for this case. The time sequence is as follows:

Ident.	Time [sec]	Action
T1	1	Pilot solenoid valve 11 is de-energized to ventilate UAP open line
T2	2	Pilot solenoid valve 12 is energized to pressurize UAP close line
T3	31	Pilot solenoid valve 13 is de-energized to ventilate LAP open line
T4	32	Pilot solenoid valve 14 is energized to pressurize LAP close line
T5	34	Pilot solenoid valve 75 is de-energized to ventilate VBR1 open line
T6	35	Pilot solenoid valve 76 is energized to pressurize VBR1 close line

Note: This case is comparable with Case 1-4

Case 2-2a: With 3000 psi pre-charge pressure in LMRP accumulators

Figure 48) shows the pressure trends and actuator positions for the two annular preventers and one VBR. The first annular preventer is “fired” to close at 2 seconds, the second preventer at 32 and the VBR at 37 seconds. This closing sequence gives a parallel operation between the last annular preventer and the VBR.

There is no difference in the actuator performance compared to the simulations performed for the system with pre-charge pressure according to specifications.

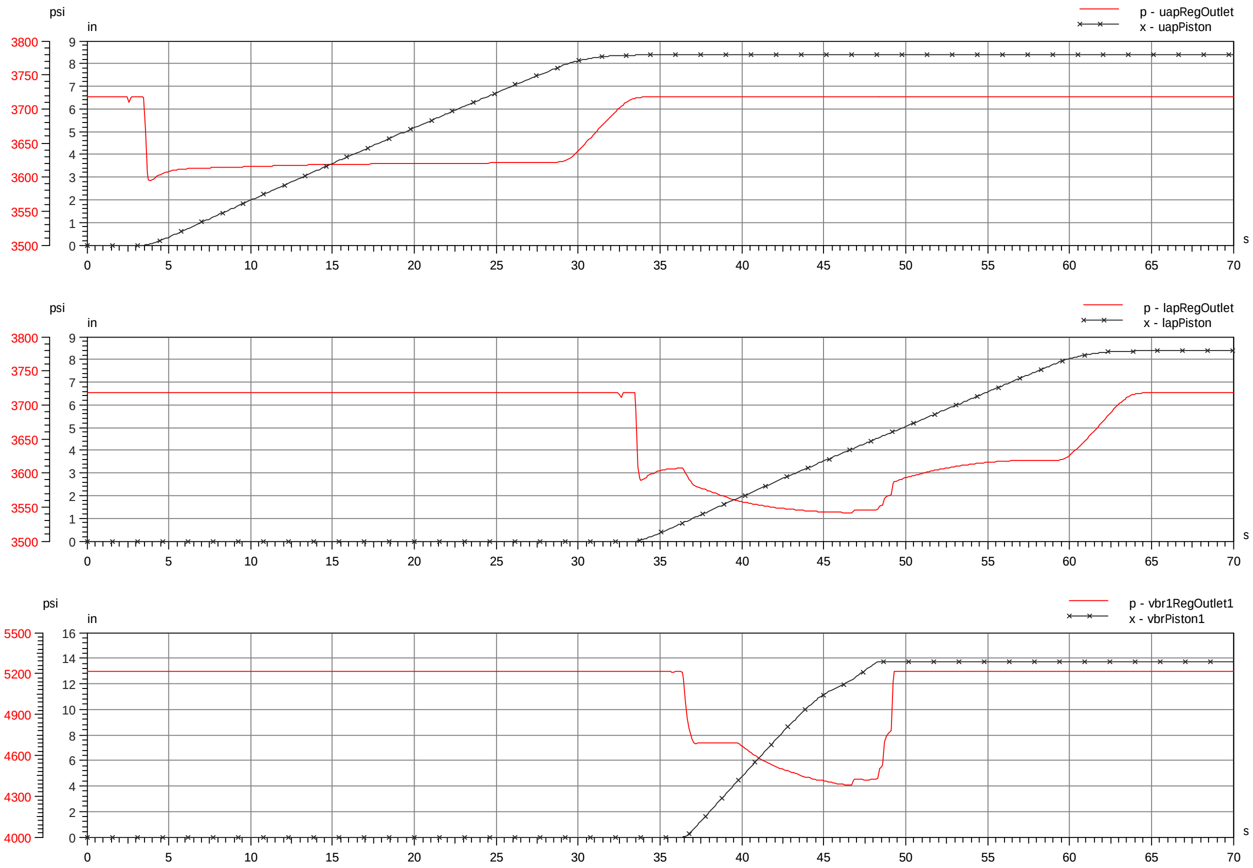


Figure 48) Pressure trends and actuator positions for Case 2-2a

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR actuator position	in

The LMRP accumulator oil volume is initially 115.7 USgal which is 31.7 USgal more than for the system pre-charged according to specifications.

When operating on annular preventer followed by a second preventer and a VBR in parallel, the LMRP accumulator oil volume drops to a minimum of 102 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 5221 psi (3003 psi + static head).

Minimum pressure is 49 psi lower than for the same system with pre-charge pressure according to specifications.

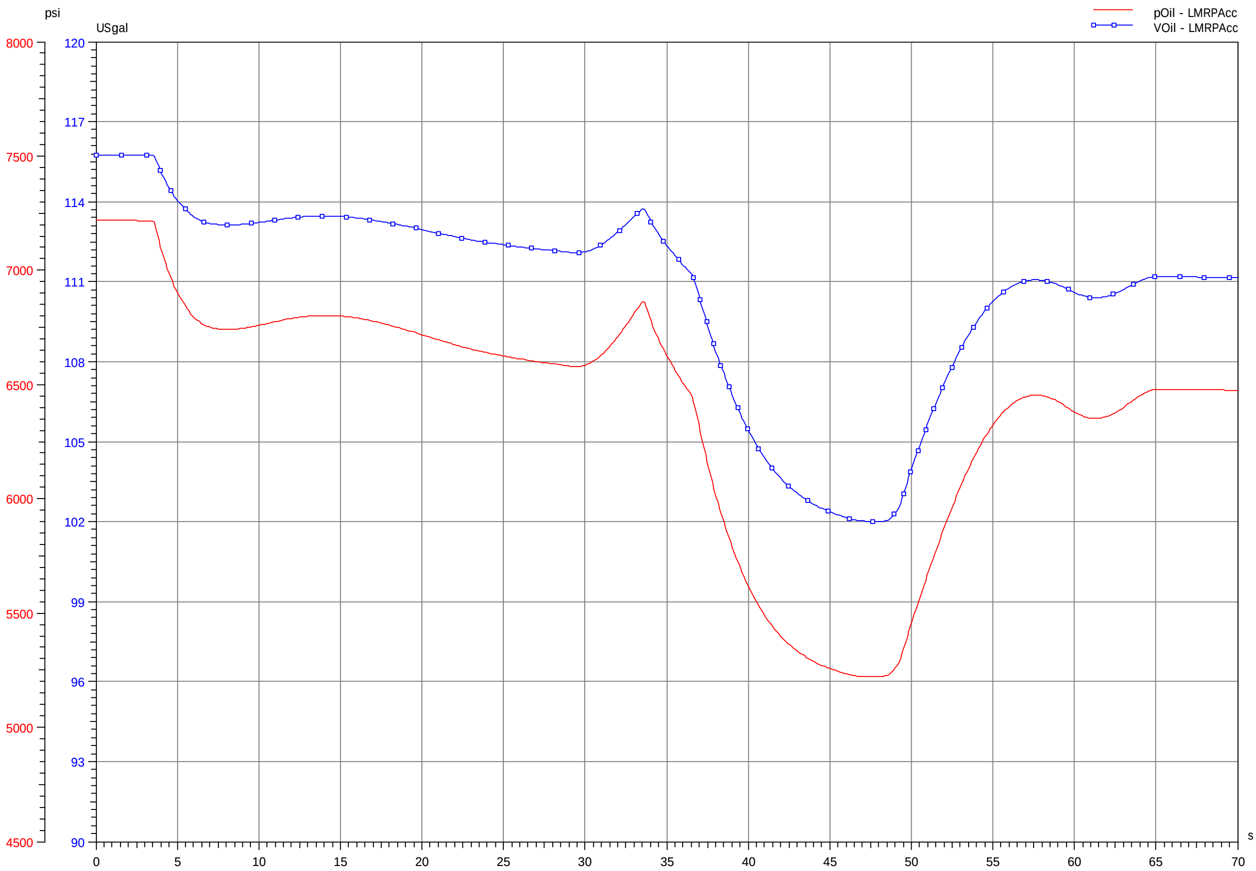


Figure 49) LMRP accumulator pressure and oil volume – Case 2-2a

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 50) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while opening one annular preventer followed by a second annular preventer and a VBR in parallel. As can be seen, the pressure drops below 4200 psi and all three pumps starts. The first pump will start at 21 seconds, the second pump at 38 seconds and the last pump at 44 seconds.

The surface system has similar pressure behaviour as for the system with LMRP accumulators pre-charged according to specifications.

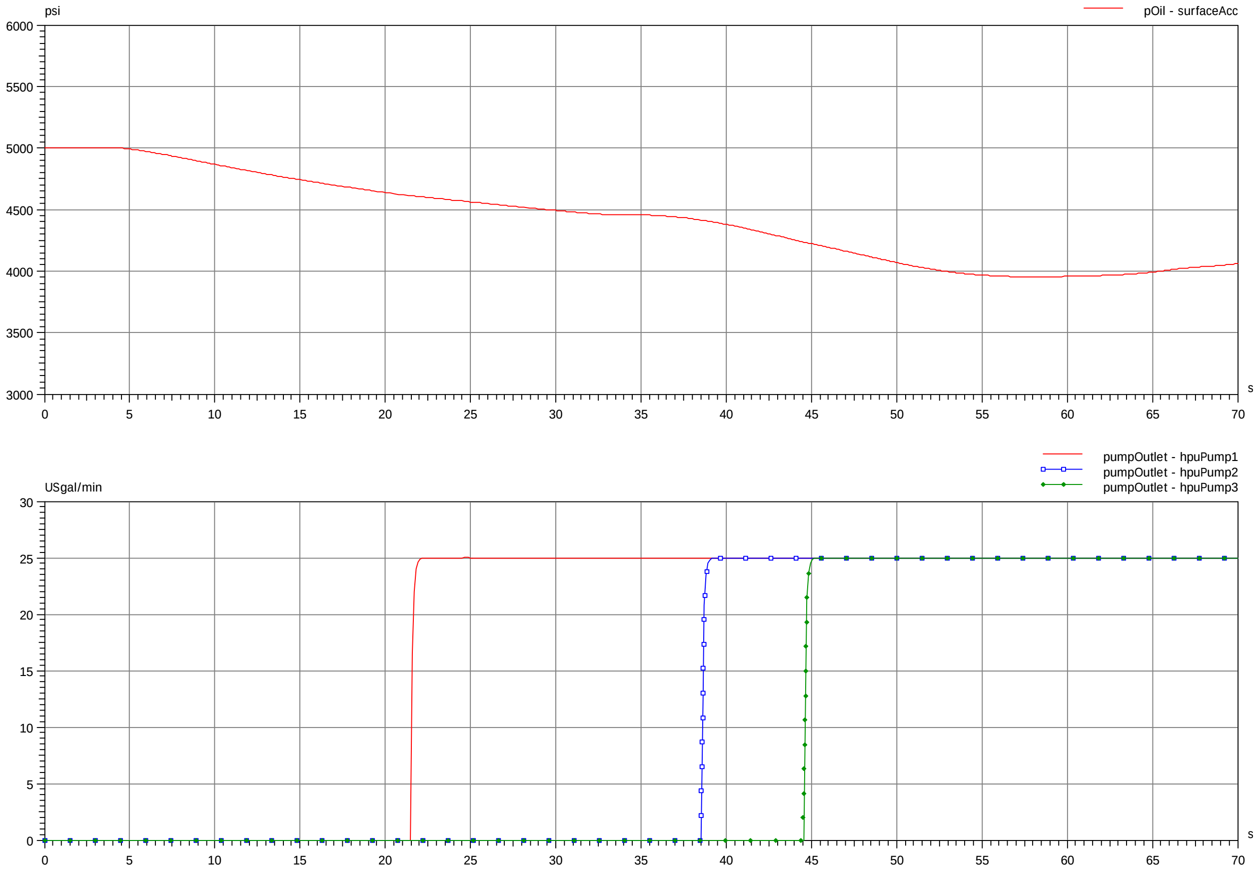


Figure 50) Surface accumulator pressure and pump flows – Case 2-2a

Legend:	Description	Unit
pOil - surfaceAcc	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

Case 2-2b: With three out of four LMRP accumulators available

Figure 51) shows the pressure trends and actuator positions for the two annular preventers and one VBR. The first annular preventer is "fired" to close at 2 seconds and the second preventer at 32 seconds and the VBR at 37 seconds which gives a parallel operation between the last annular preventer and the VBR.

There is no difference in the actuator performance compared to the simulations performed for the system with pre-charge pressure according to specifications.

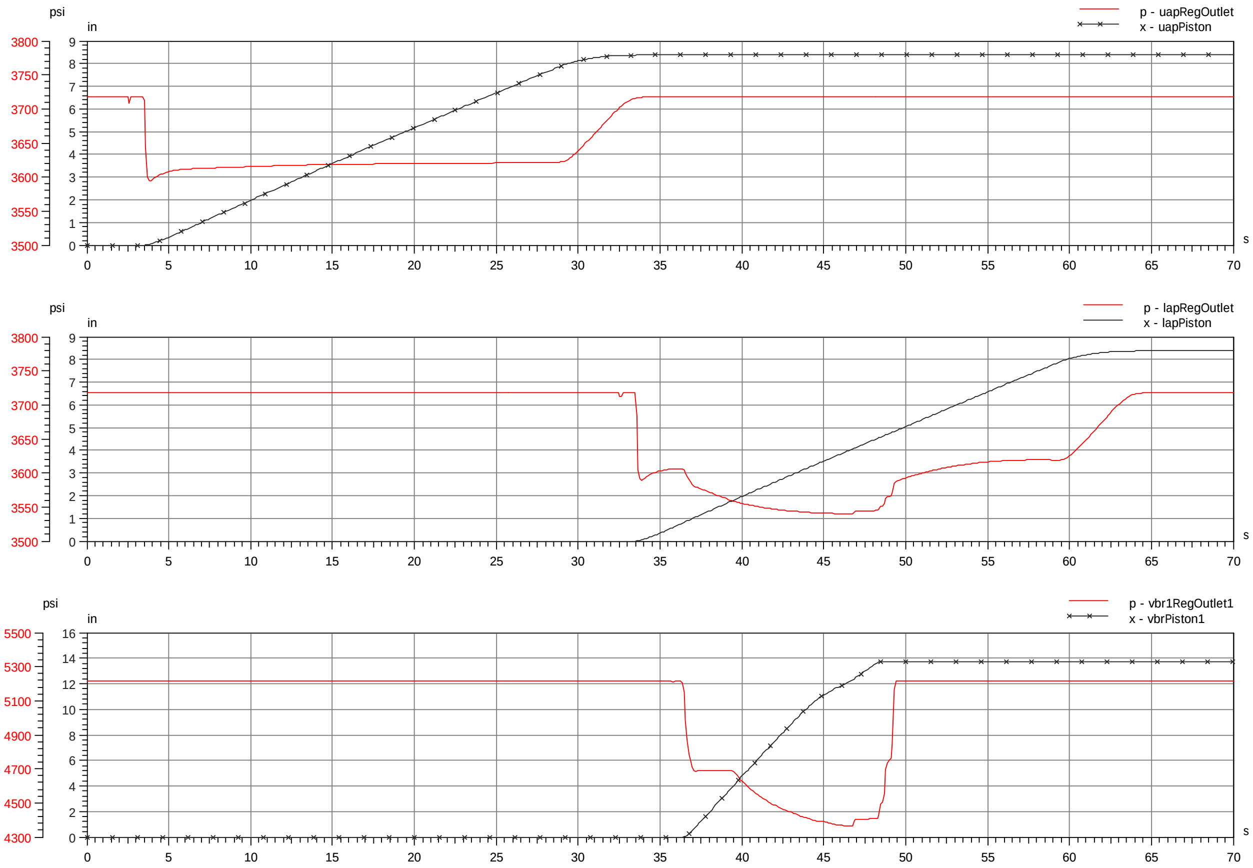


Figure 51) Pressure trends and actuator positions for Case 2-2b

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR actuator position	in

The LMRP accumulator oil volume is initially 63.2 USgal which is 20.8 USgal less than for the same system with all four accumulators available.

When operating one annular preventer followed by a second preventer and one VBR in parallel, the LMRP accumulator oil volume drops to a minimum of 50.2 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 5200 psi (2982 psi + static head).

Minimum pressure is 70 psi lower than for the same system with all four accumulators available.

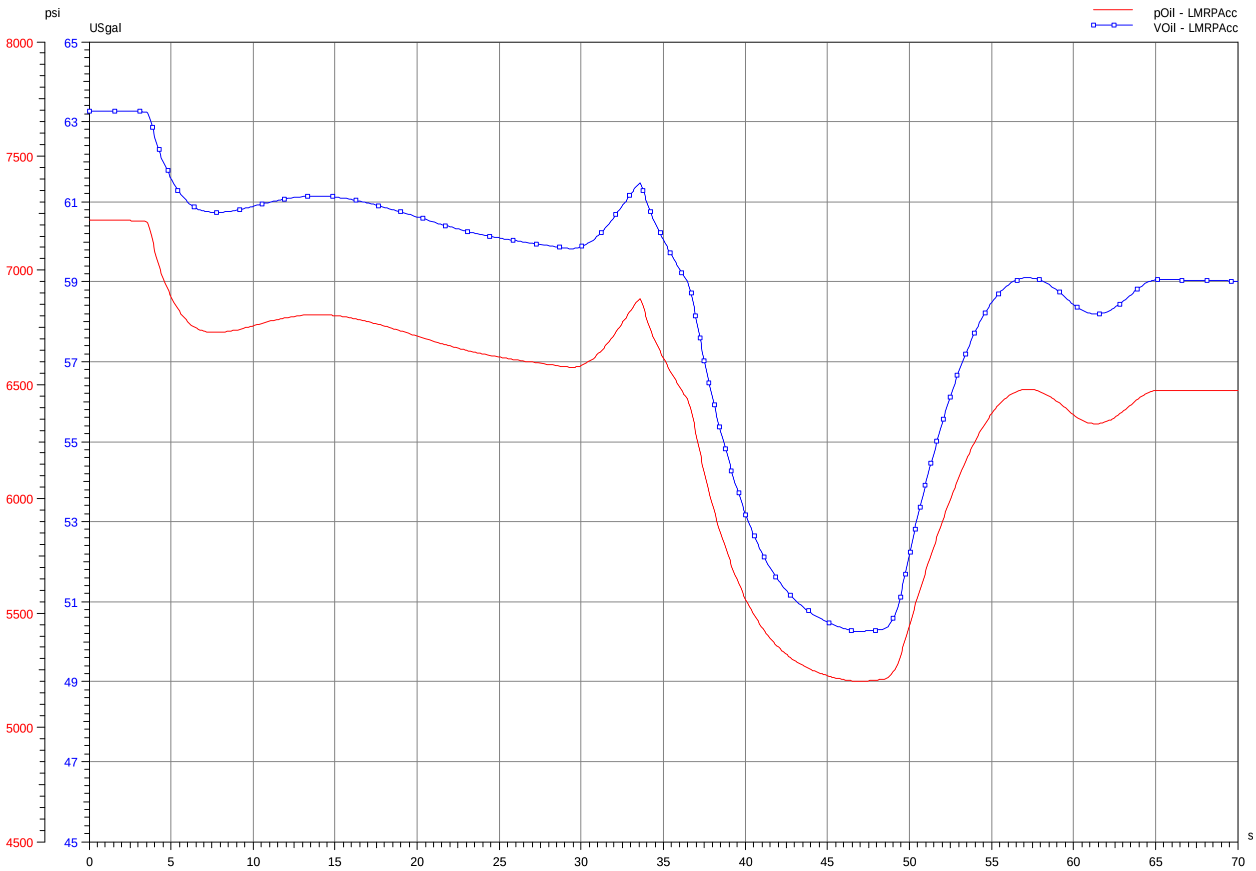


Figure 52) LMRP accumulator pressure and oil volume – Case 2-2b

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 53) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while opening one annular preventer followed by a second annular preventer and a VBR in parallel. As can be seen, the pressure drops below 4200 psi and all three pumps starts. The first pump will start at 21 seconds, the second pump at 38 seconds and the last pump at 44 seconds.

The surface system similar pressure behaviour as for the system with LMRP accumulators pre-charged according to specifications.

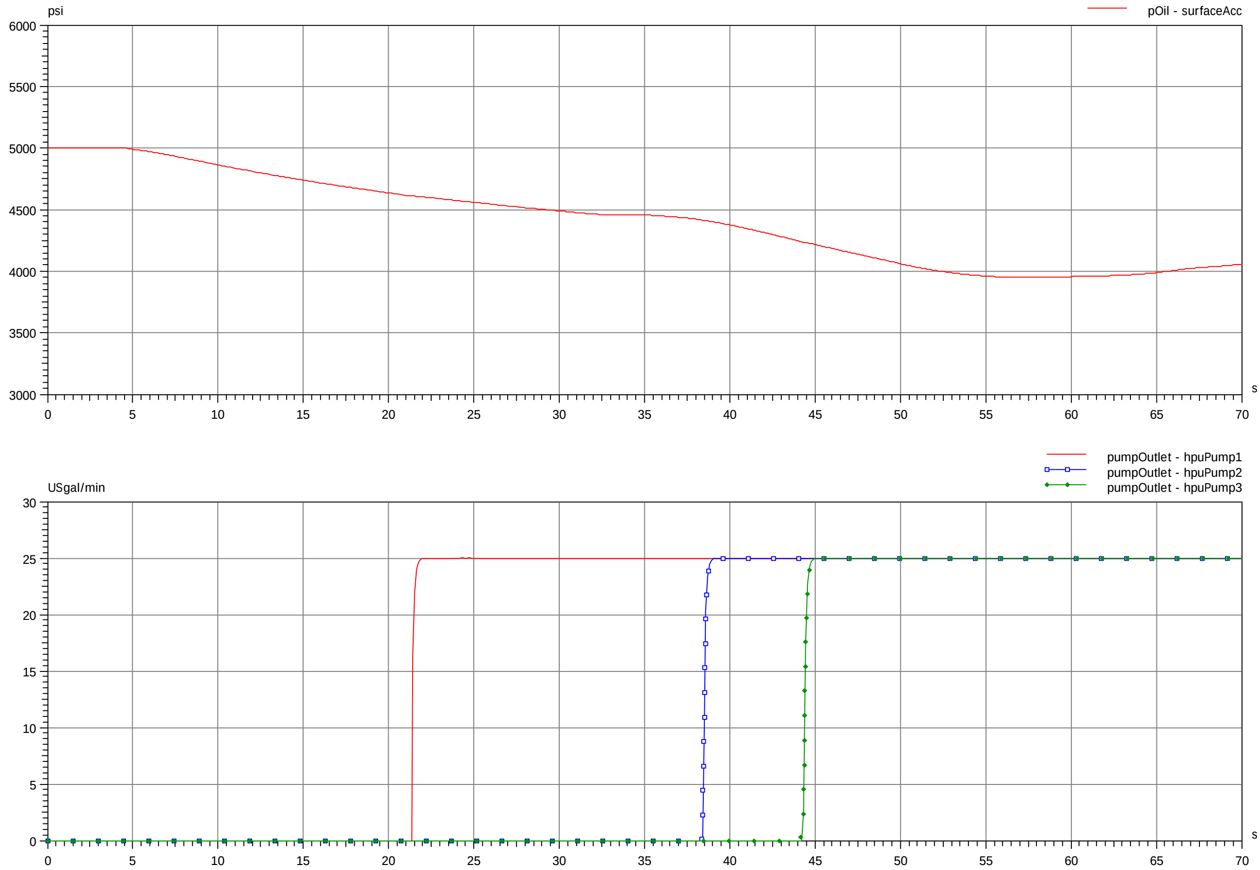


Figure 53) Surface accumulator pressure and pump flows – Case 2-2b

Legend:	Description	Unit
pOil - surface	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.2.3 Case 2-3: Closing UAP followed by LAP and two VBR's in parallel

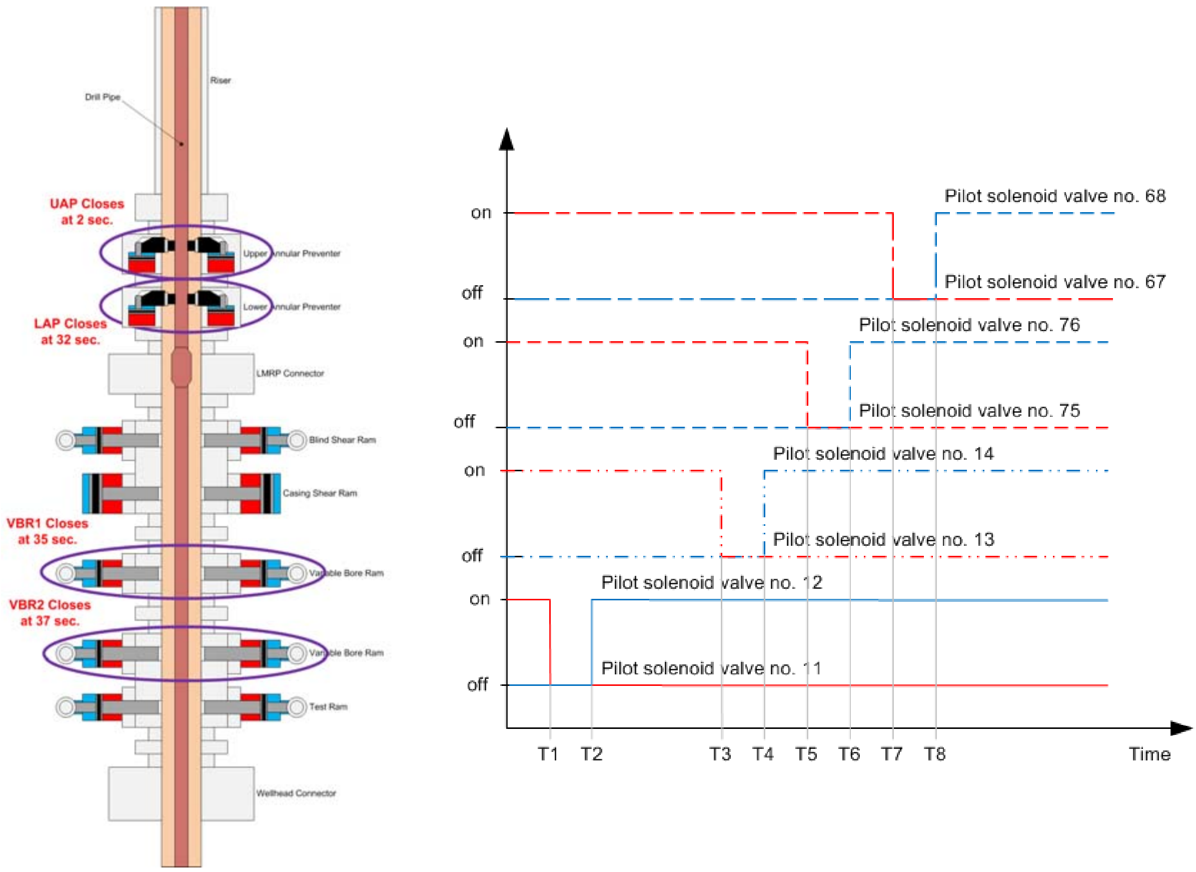


Figure 54) Valve Operation Scheme for Case 2-3

Figure 54) shows the operation of the pilot solenoid valves in the control pod for this case. The time sequence is as follows:

Ident.	Time [sec]	Action
T1	1	Pilot solenoid valve 11 is de-energized to ventilate UAP open line
T2	2	Pilot solenoid valve 12 is energized to pressurize UAP close line
T3	31	Pilot solenoid valve 13 is de-energized to ventilate LAP open line
T4	32	Pilot solenoid valve 14 is energized to pressurize LAP close line
T5	34	Pilot solenoid valve 75 is de-energized to ventilate VBR1 open line
T6	35	Pilot solenoid valve 76 is energized to pressurize VBR1 close line
T7	36	Pilot solenoid valve 67 is de-energized to ventilate VBR2 open line
T8	37	Pilot solenoid valve 68 is energized to pressurize VBR2 close line

Note: This case is comparable with Case 1-5

5.2.3.1 Case 2-3a: With 3000 psi pre-charge pressure in LMRP accumulators

Figure 55) shows the pressure trends and actuator positions for the two annular preventers and two VBR's. The first annular preventer is "fired" to close at 2 seconds, the second annular at 32 seconds, the first VBR at 37 seconds and the second VBR at 38 seconds which gives a parallel operation between the last annular preventer and the VBR's.

There is no difference in the actuator performance compared to the simulations performed for the system with pre-charge pressure according to specifications.

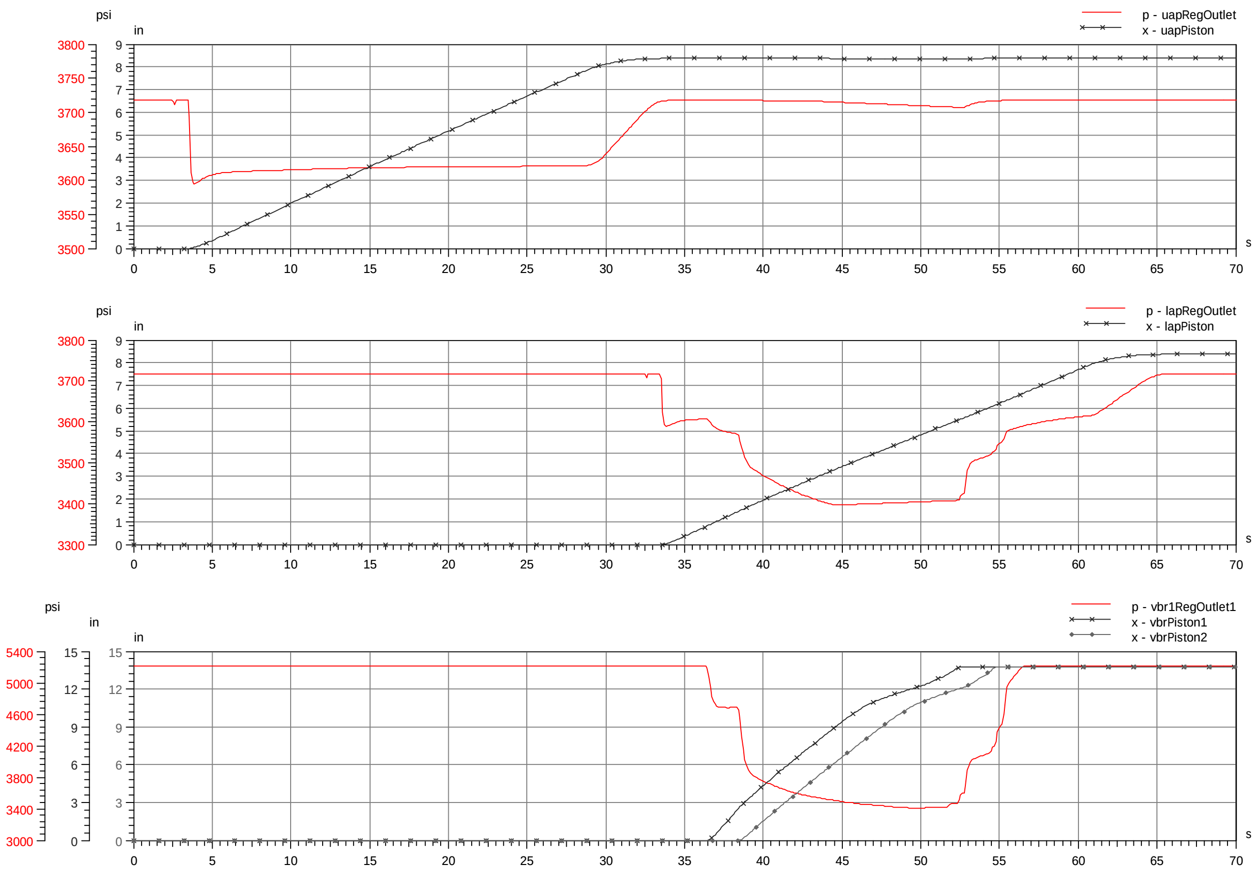


Figure 55) Pressure trends and actuator positions for Case 2-3a

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR1 actuator position	in
x – vbrPiston2	VBR2 actuator position	in

The LMRP accumulator oil volume is initially 115.7 USgal which is 31.7 USgal more than for the system pre-charged according to specifications.

When operating one annular preventer followed by a second annular preventer with two VBR's in parallel, the LMRP accumulator oil volume drops to a minimum of 96.3 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 4657 psi (2439 psi + static head).

Minimum pressure is 43 psi lower than for the same system with pre-charge pressure according to specifications.

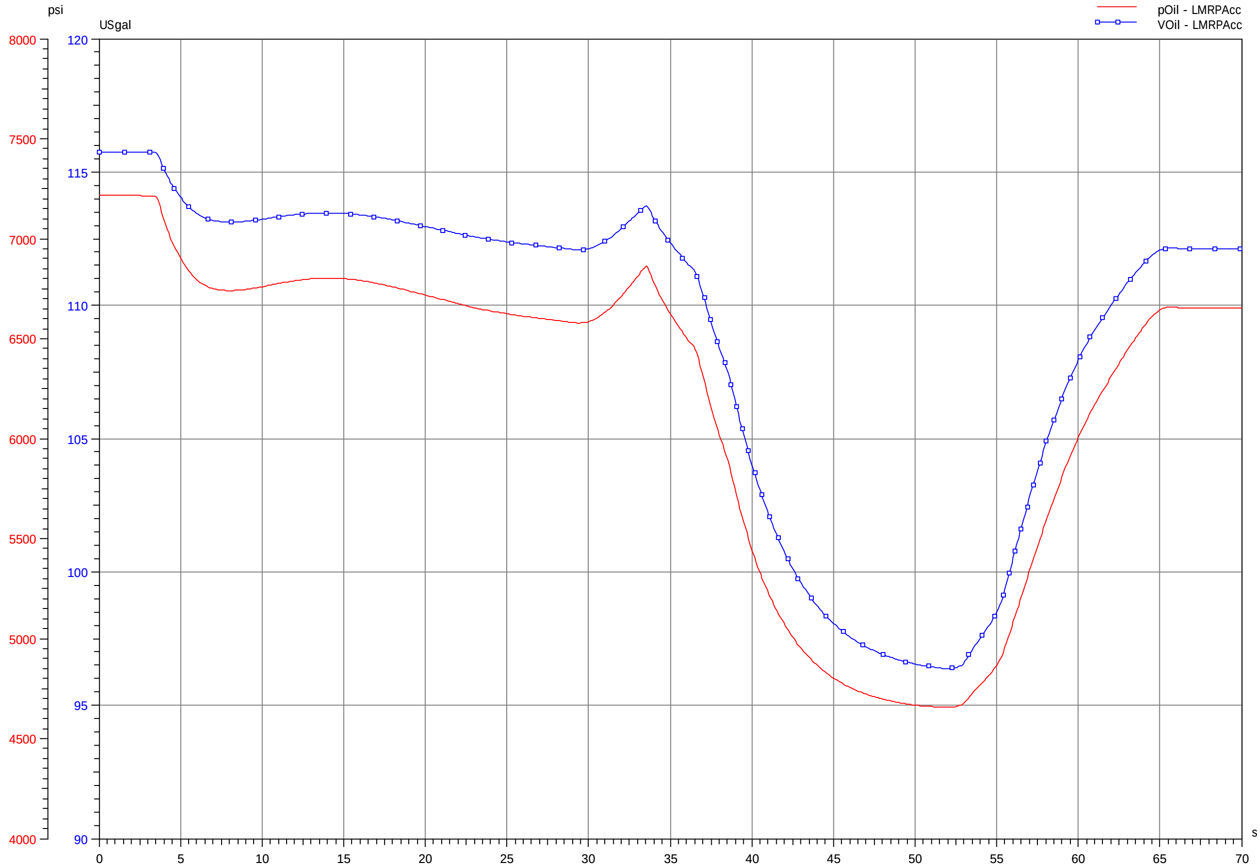


Figure 56) LMRP accumulator pressure and oil volume – Case 2-3a

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 57) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while opening one annular preventer followed by a second annular preventer and two VBR's in parallel. As can be seen, the pressure drops below 4200 psi and all three pumps starts. The first pump will start at 21 seconds, the second pump at 38 seconds and the last pump at 43 seconds.

The surface system has similar pressure behaviour as for the system with LMRP accumulators pre-charged according to specifications.

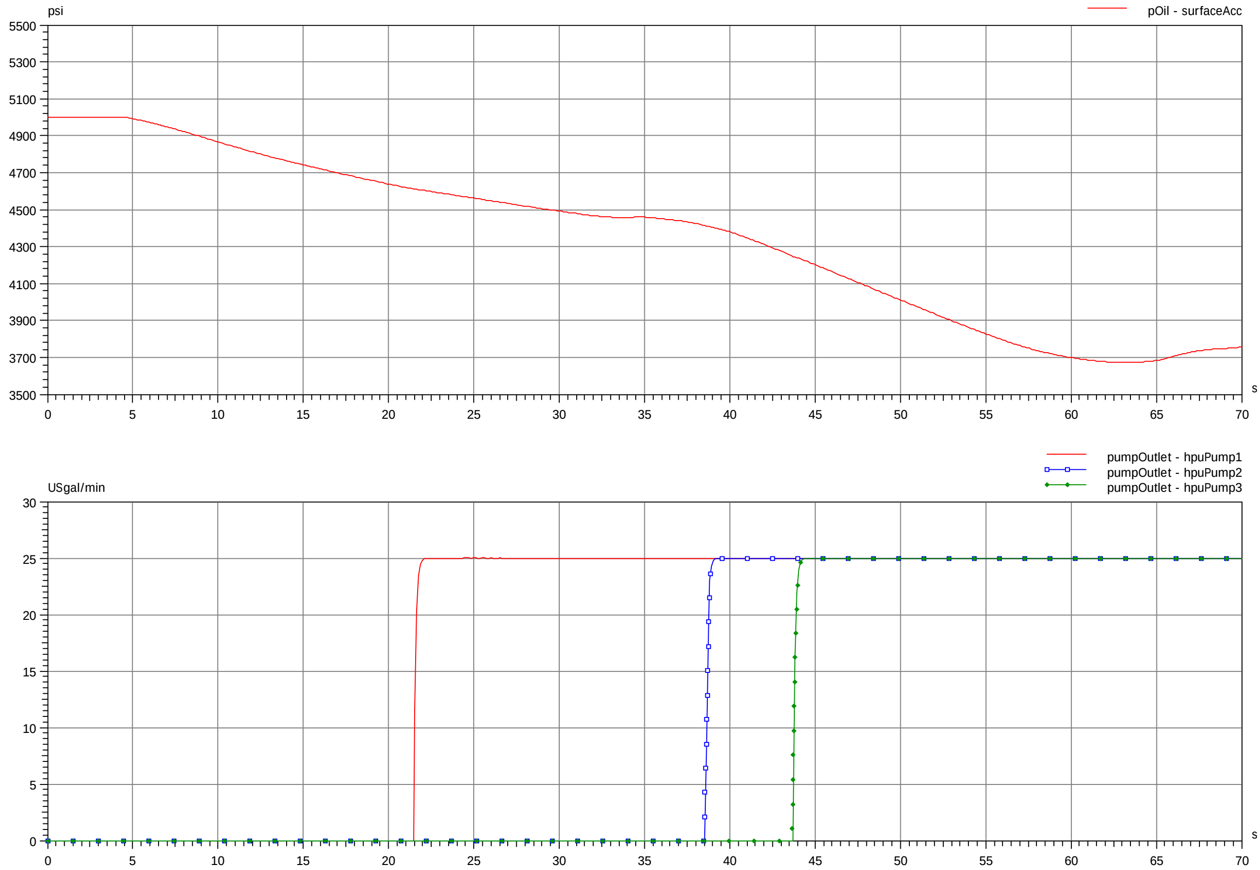


Figure 57) Surface accumulator pressure and pump flows – 2-3a

Legend:	Description	Unit
pOil - surface	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.2.3.2 Case 2-3b: With three out of four LMRP accumulators available

Figure 58) shows the pressure trends and actuator positions for the two annular preventers and two VBR's. The first annular preventer is "fired" to open at 2 seconds, the second preventer at 32 seconds, the first VBR at 34 seconds and the second VBR at 36 seconds. This valve opening sequence gives parallel operation between the last annular preventer and the VBR's.

There is no difference in the actuator performance compared to the simulations performed for the system with pre-charge pressure according to specifications.

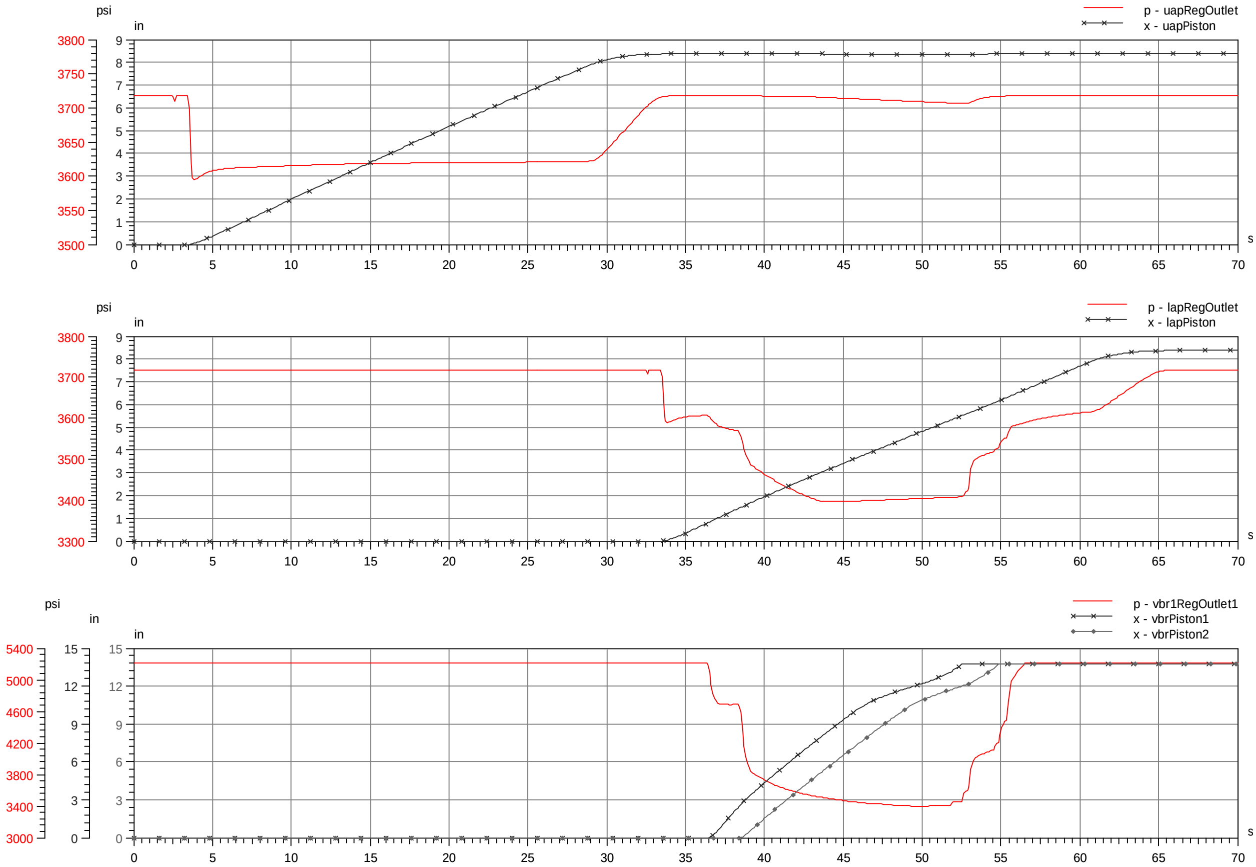


Figure 58) Pressure trends and actuator positions for Case 2-3b

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR1 actuator position	in
x – vbrPiston2	VBR2 actuator position	in

The LMRP accumulator oil volume is initially 63.2 USgal which is 20.8 USgal less than for the same system with all four accumulators available.

When operating the one annular preventer followed by the second preventer and two VBR’s in parallel, the LMRP accumulator oil volume drops to a minimum of 45 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 4642 psi (2424 psi + static head).

Minimum pressure is 58 psi lower than for the same system with all four accumulators available.

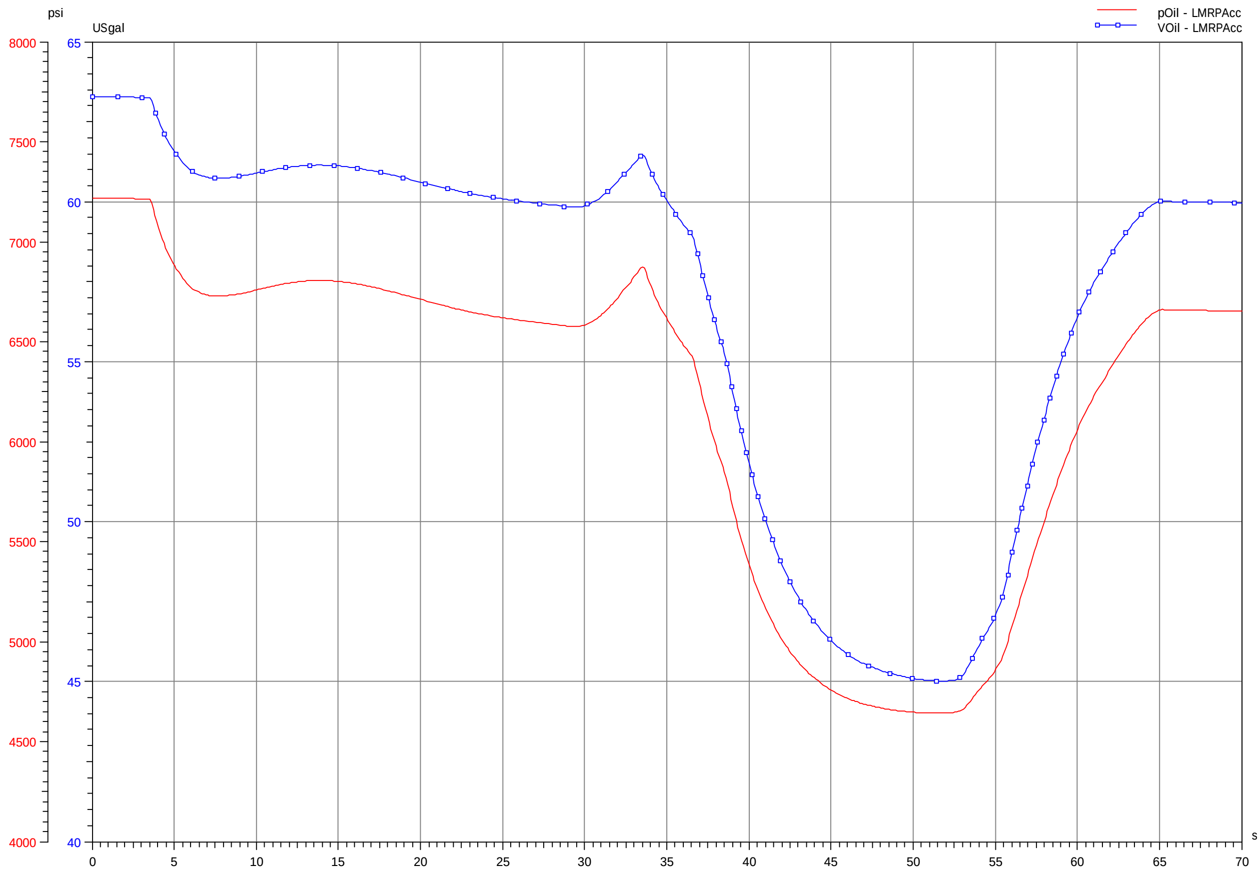


Figure 59) LMRP accumulator pressure and oil volume – Case 2-3b

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 60) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while opening one annular preventer followed by a second annular preventer and two VBR's in parallel. As can be seen, the pressure drops below 4200 psi and all three pumps starts. The first pump will start at 21 seconds, the second pump at 38 seconds and the last pump at 43 seconds.

The surface system has similar pressure behaviour as for the system with LMRP accumulators pre-charged according to specifications.

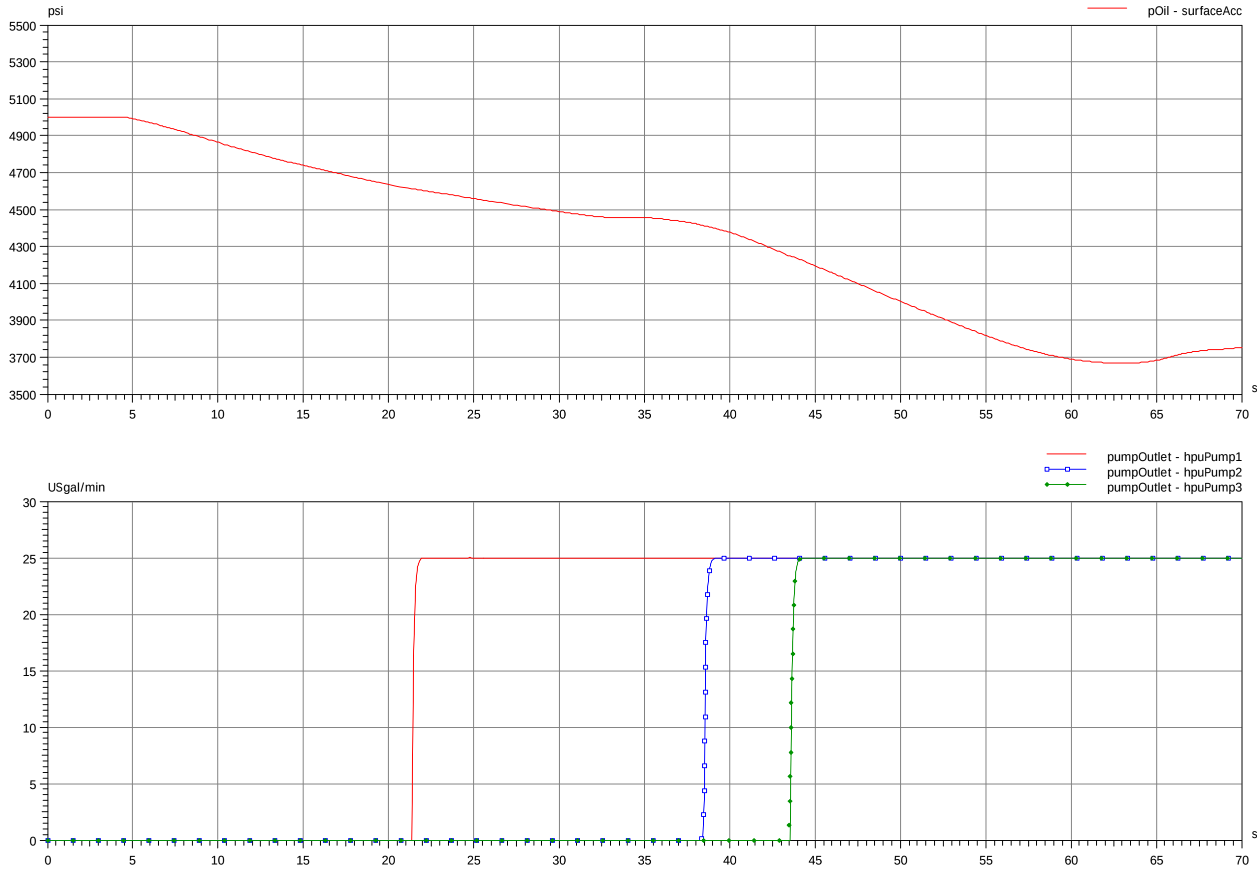
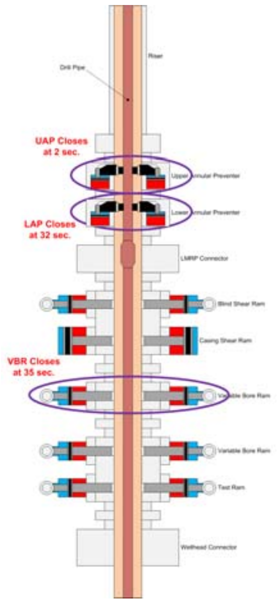


Figure 60) Surface accumulator pressure and pump flows – 2-3b

Legend:	Description	Unit
pOil - surfaceAcc	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.2.4 Case 2-4: Closing UAP, LAP and one VBR in parallel



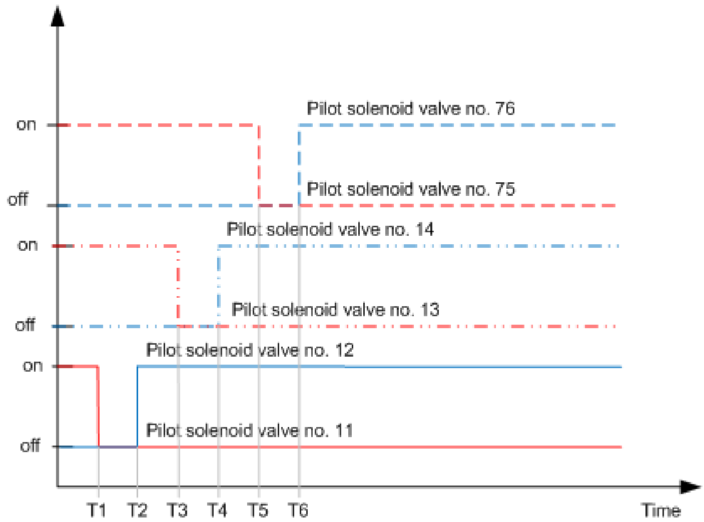


Figure 61) Valve Operation Scheme for Case 2-4

Figure 61) shows the operation of the pilot solenoid valves in the control pod for this case. The time sequence is as follows:

Ident.	Time [sec]	Action
T1	1	Pilot solenoid valve 11 is de-energized to ventilate UAP open line
T2	2	Pilot solenoid valve 12 is energized to pressurize UAP close line
T3	3	Pilot solenoid valve 13 is de-energized to ventilate LAP open line
T4	4	Pilot solenoid valve 14 is energized to pressurize LAP close line
T5	5	Pilot solenoid valve 75 is de-energized to ventilate VBR1 open line
T6	6	Pilot solenoid valve 76 is energized to pressurize VBR1 close line

Note: This case is comparable with Case 1-6

5.2.4.1 Case 2-4a: With 3000 psi pre-charge pressure in LMRP accumulators

Figure 62) shows the pressure trends and actuator positions for the two annular preventers and one VBR. The first annular preventer is “fired” to open at 2 seconds, the second annular at 4 seconds and the VBR at 6 seconds. This gives a parallel operation of all three valve actuators.

There is no difference in the actuator performance compared to the simulations performed for the system with pre-charge pressure according to specifications.

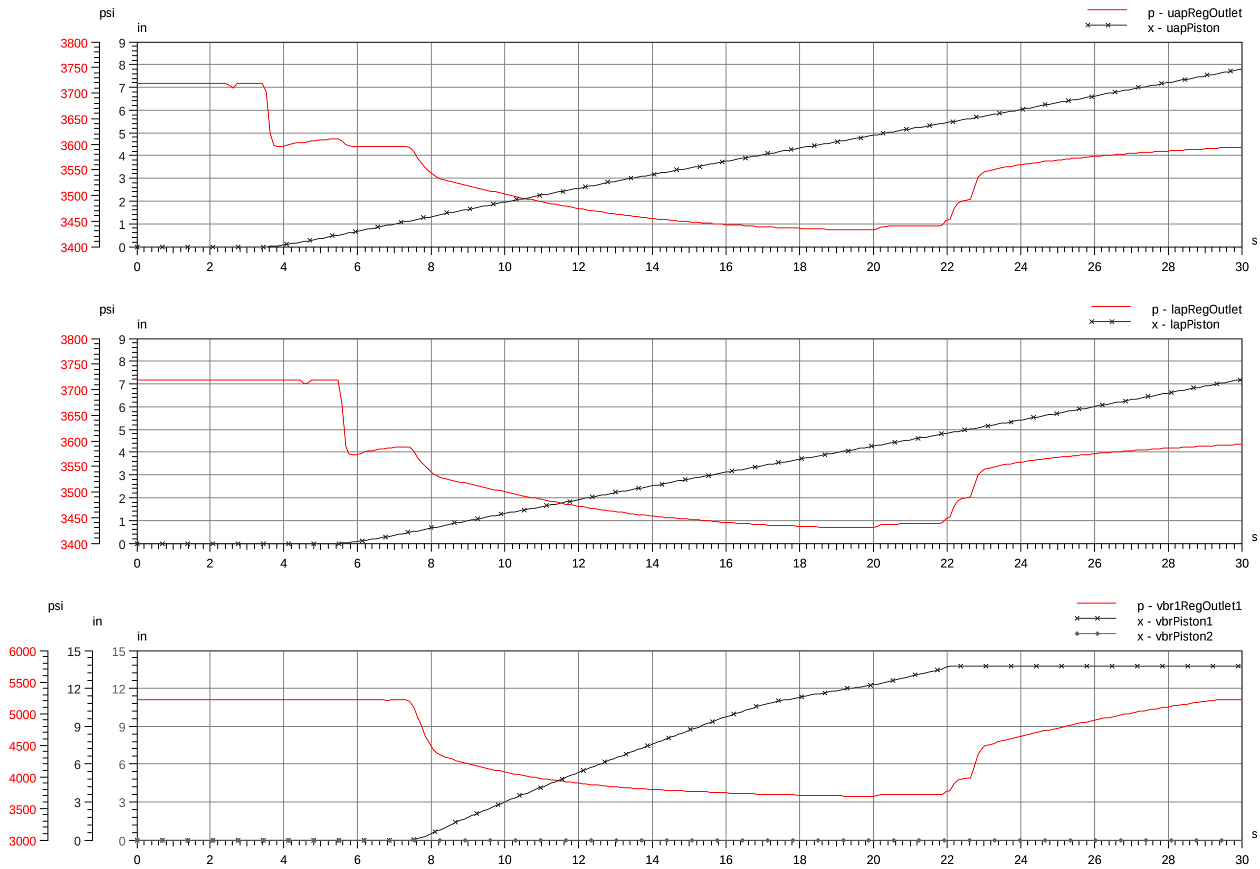


Figure 62) Pressure trends and actuator positions for Case 2-4a

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR1 actuator position	in
x – vbrPiston2	VBR2 actuator position	in

The LMRP accumulator oil volume is initially 115.7 USgal which is 31.7 USgal more than for the system pre-charged according to specifications.

When operating two annular preventers and a VBR in parallel, the LMRP accumulator oil volume drops to a minimum of 99 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 4904 psi (2686 psi + static head).

Minimum pressure is 42 psi lower than for the same system with pre-charge pressure according to specifications.

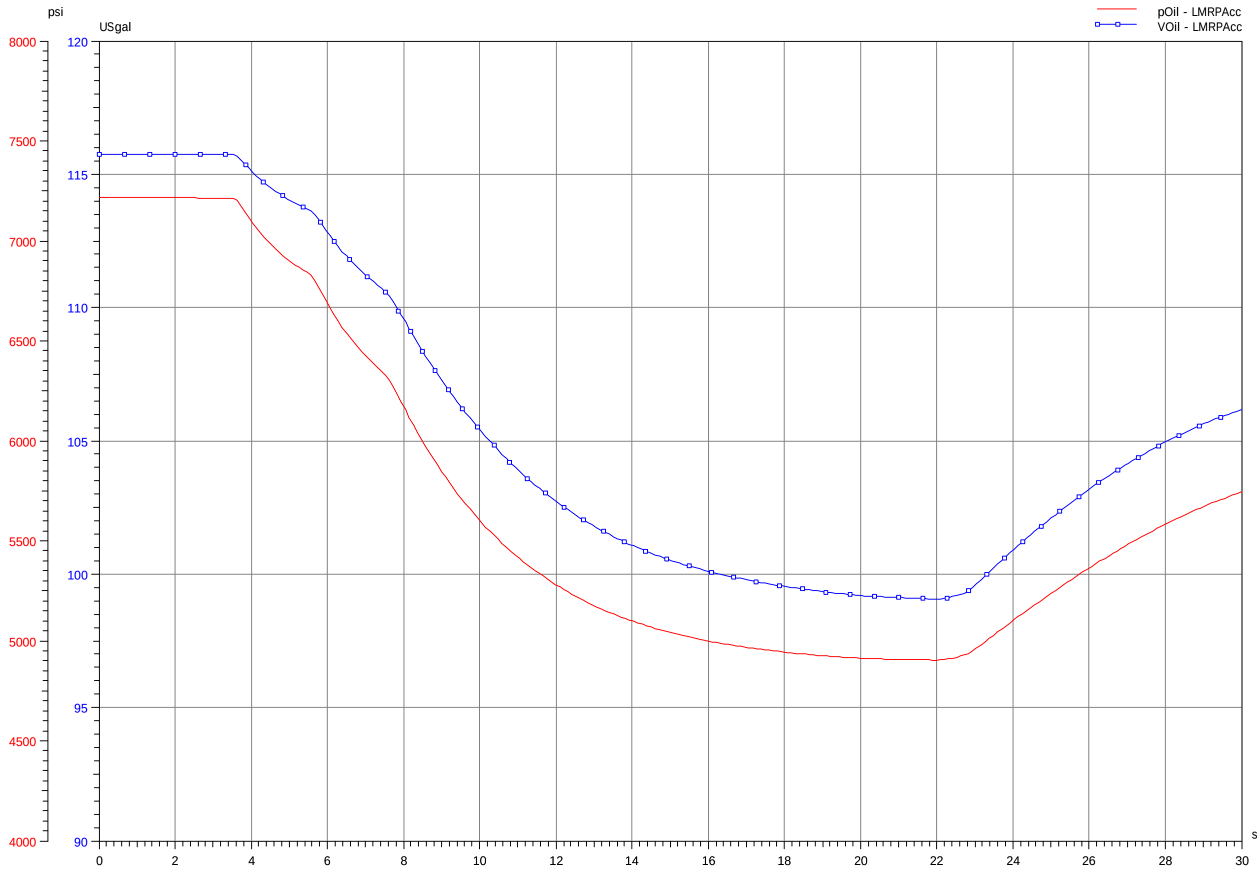


Figure 63) LMRP accumulator pressure and oil volume – Case 2-4a

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 64) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while opening two annular preventer and a VBR in parallel. As can be seen, the pressure drops below 4200 psi and all three pumps starts. The first pump will start at 12 seconds, the second pump at 16 seconds and the last pump at 20 seconds.

The surface system has the same pressure behaviour as for the system with LMRP accumulators pre-charged according to specifications.

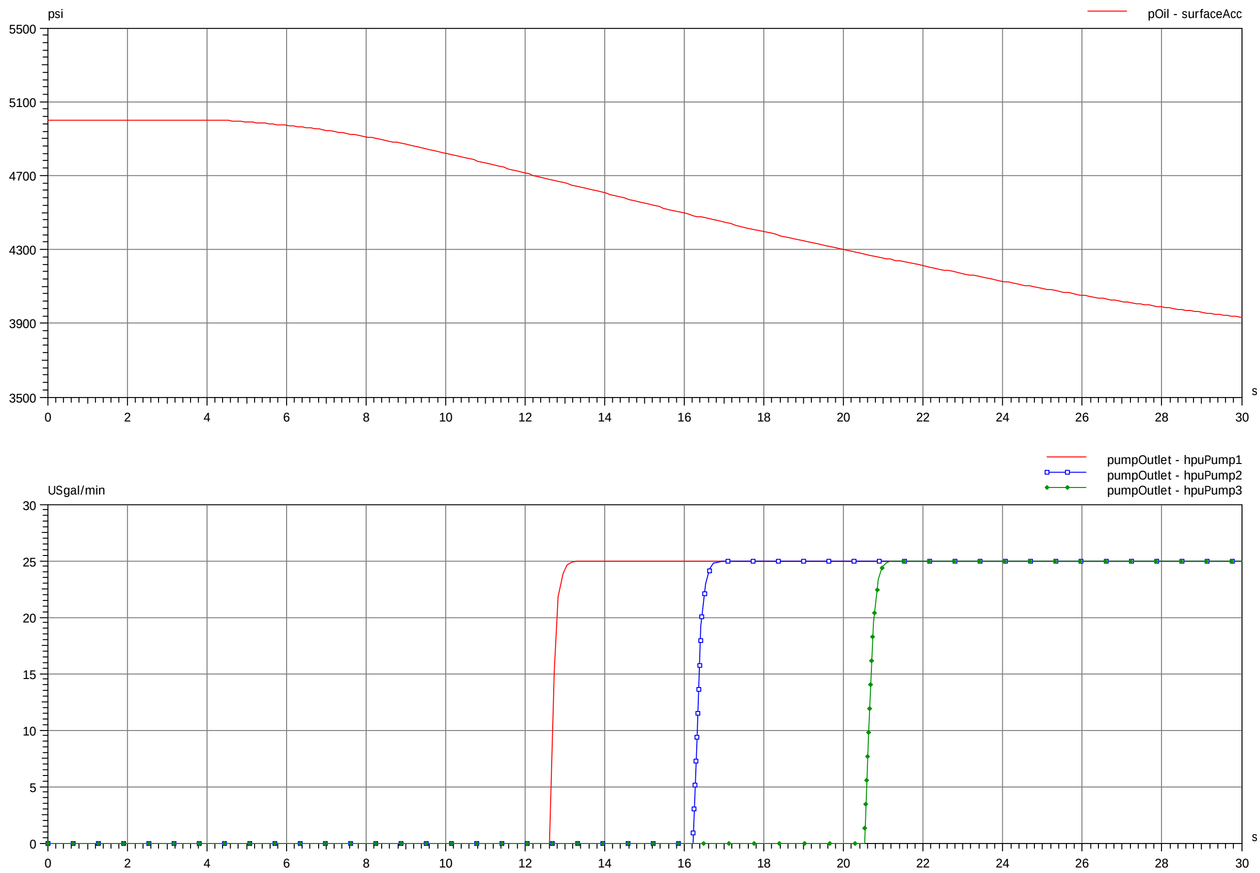


Figure 64) Surface accumulator pressure and pump flows – 2-4a

Legend:	Description	Unit
pOil - surfaceAcc	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.2.4.2 Case 2-4b: With three out of four LMRP accumulators available

Figure 65) shows the pressure trends and actuator positions for the two annular preventers and one VBR. The first annular preventer is “fired” to open at 2 seconds, the second annular at 4 seconds and the VBR at 6 seconds. This gives a parallel operation of all three valve actuators.

There is no difference in the actuator performance compared to the simulations performed for the system with pre-charge pressure according to specifications.

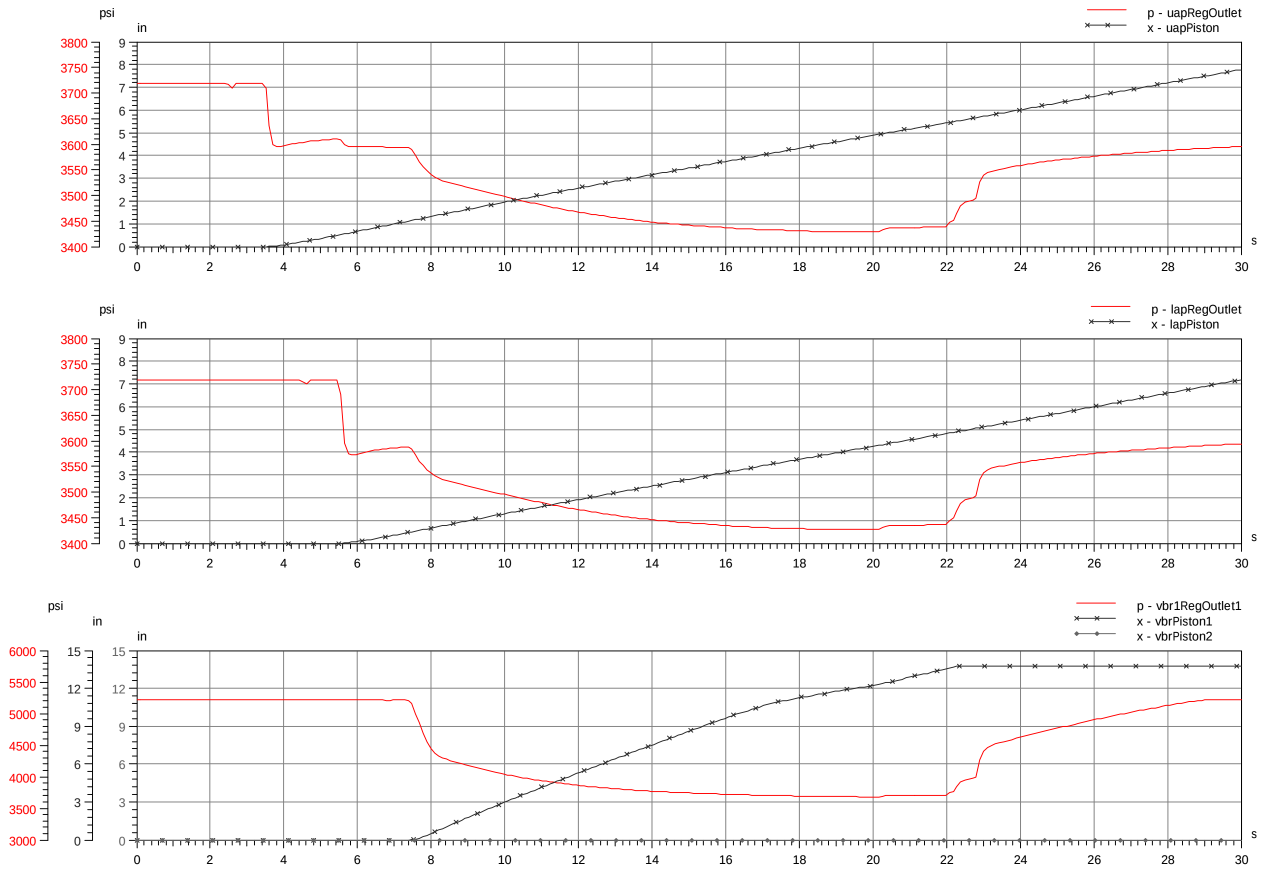


Figure 65) Pressure trends and actuator positions for Case 2-4b

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR1 actuator position	in
x – vbrPiston2	VBR2 actuator position	in

The LMRP accumulator oil volume is initially 63.2 USgal which is 20.8 USgal less than for the same system with all four accumulators available.

When operating the two annular preventers and a VBR in parallel, the LMRP accumulator oil volume drops to a minimum of 47.5 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 4891 psi (2673 psi + static head).

Minimum pressure is 55 psi lower than for the same system with all four accumulators available.

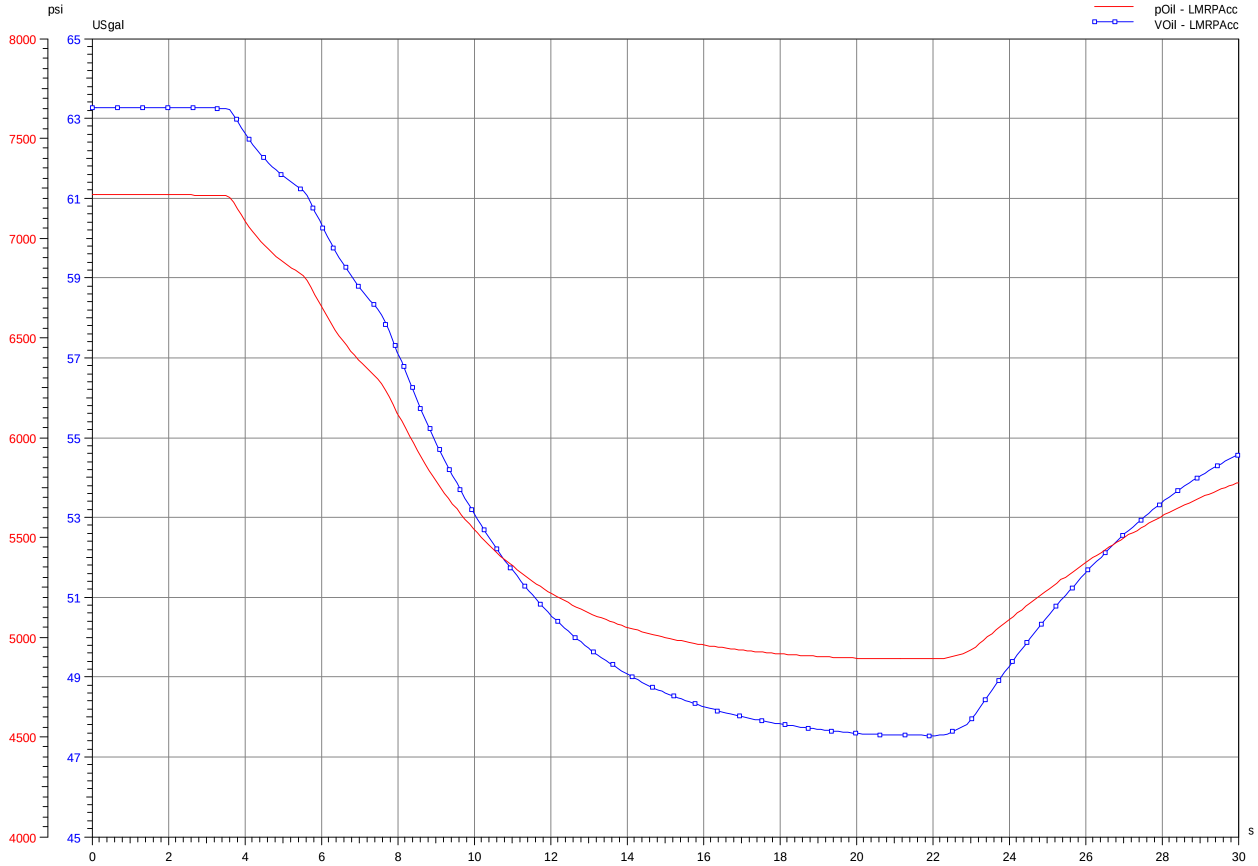


Figure 66) LMRP accumulator pressure and oil volume – Case 2-4b

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 67) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while operating two annular preventers and two VBR's in parallel. As can be seen, the pressure drops below 4200 psi and all three pumps starts. The first pump will start at 12 seconds, the second pump at 16 seconds and the last pump at 20 seconds.

The surface system has the same pressure behaviour as for the system with LMRP accumulators pre-charged according to specifications.

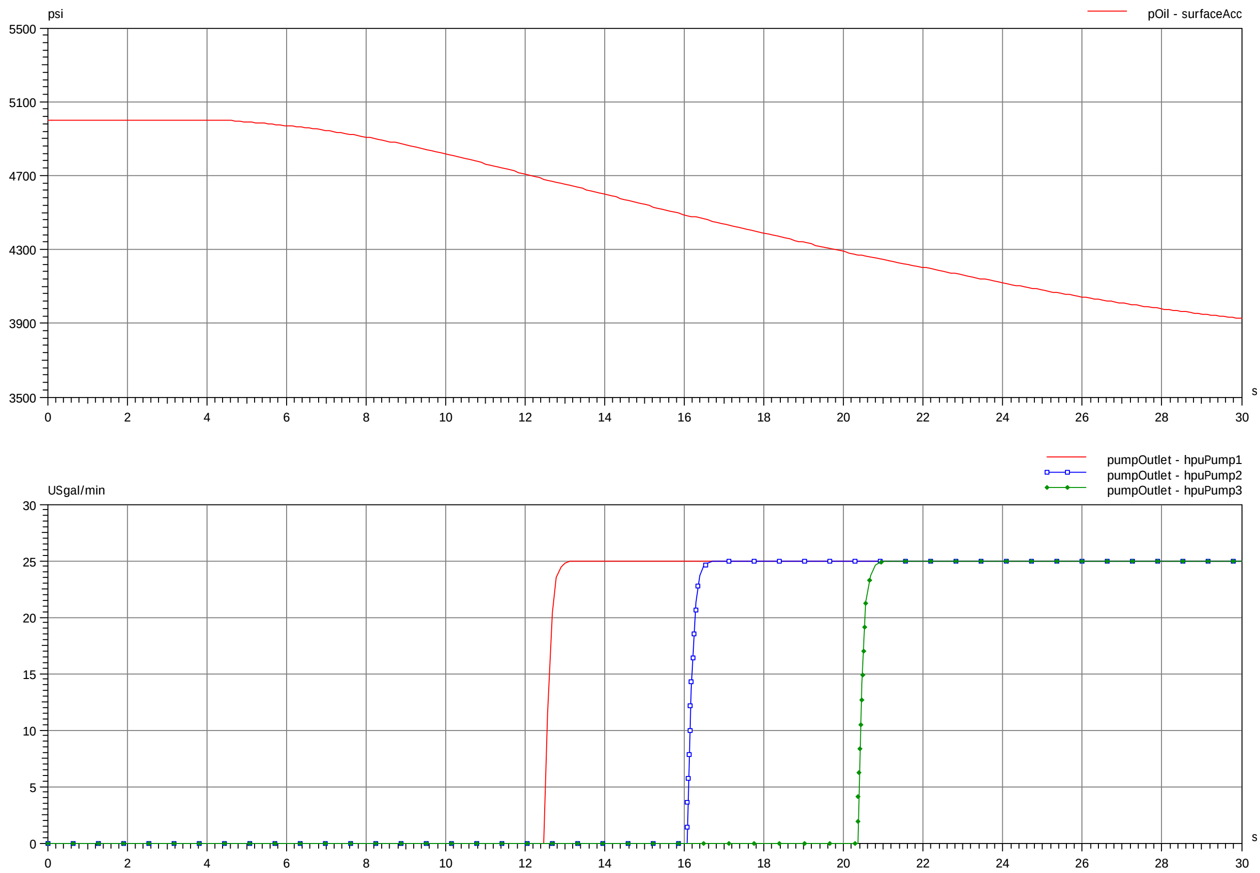


Figure 67) Surface accumulator pressure and pump flows – 2-4b

Legend:	Description	Unit
pOil - surface	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.2.5 Case 2-5: Closing UAP, LAP and two VBR's in parallel

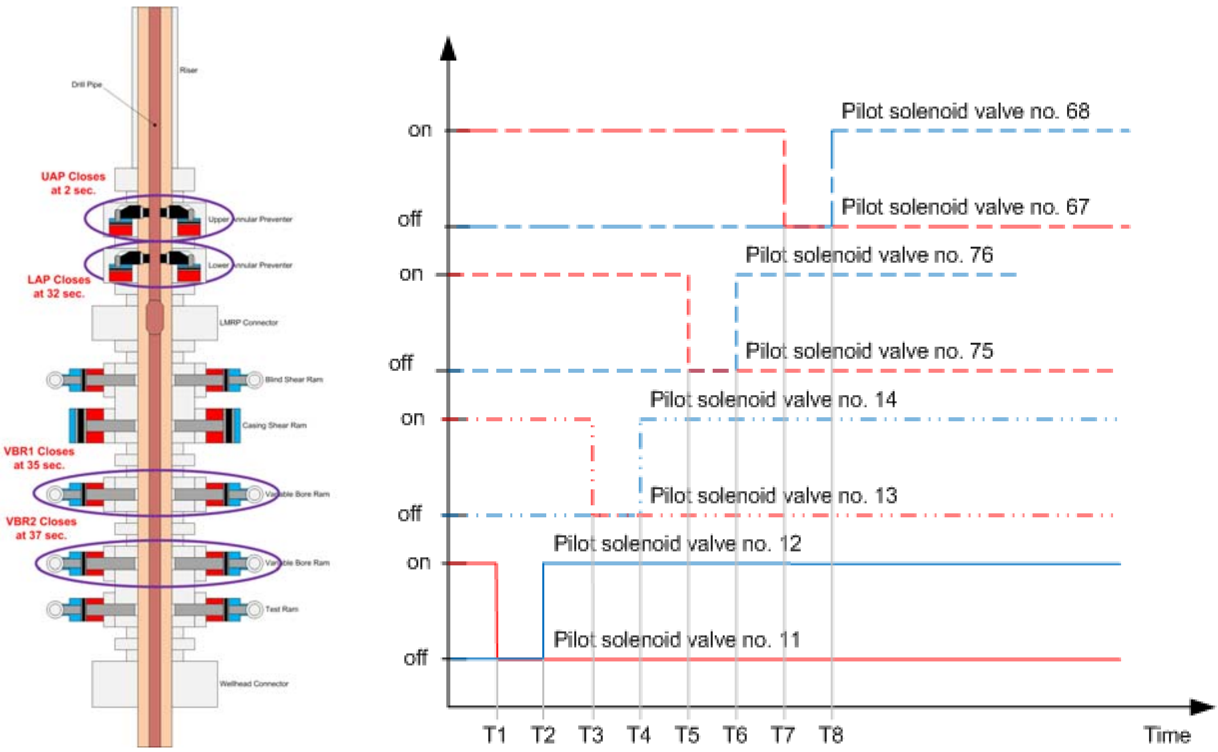


Figure 68) Valve Operation Scheme for Case 2.5

Figure 68) shows the operation of the pilot solenoid valves in the control pod for this case. The time sequence is as follows:

Ident.	Time [sec]	Action
T1	1	Pilot solenoid valve 11 is de-energized to ventilate UAP open line
T2	2	Pilot solenoid valve 12 is energized to pressurize UAP close line
T3	3	Pilot solenoid valve 13 is de-energized to ventilate LAP open line
T4	4	Pilot solenoid valve 14 is energized to pressurize LAP close line
T5	5	Pilot solenoid valve 75 is de-energized to ventilate VBR1 open line
T6	6	Pilot solenoid valve 76 is energized to pressurize VBR1 close line
T7	7	Pilot solenoid valve 67 is de-energized to ventilate VBR2 open line
T8	8	Pilot solenoid valve 68 is energized to pressurize VBR2 close line

Note: This case is comparable with Case 1-7

5.2.5.1 Case 2-5a: With 3000 psi pre-charge pressure in LMRP accumulators

Figure 69) shows the pressure trends and actuator positions for the two annular preventers and the two VBR's. The first annular preventer is "fired" to open at 2 seconds, the second annular at 4 seconds, the first VBR at 6 seconds and the second VBR at 8 seconds. This gives a parallel operation of all four valve actuators.

There is a small difference in the actuator performance compared to the simulations performed for the system with pre-charge pressure according to specifications. The difference is less than a second for the last VBR.

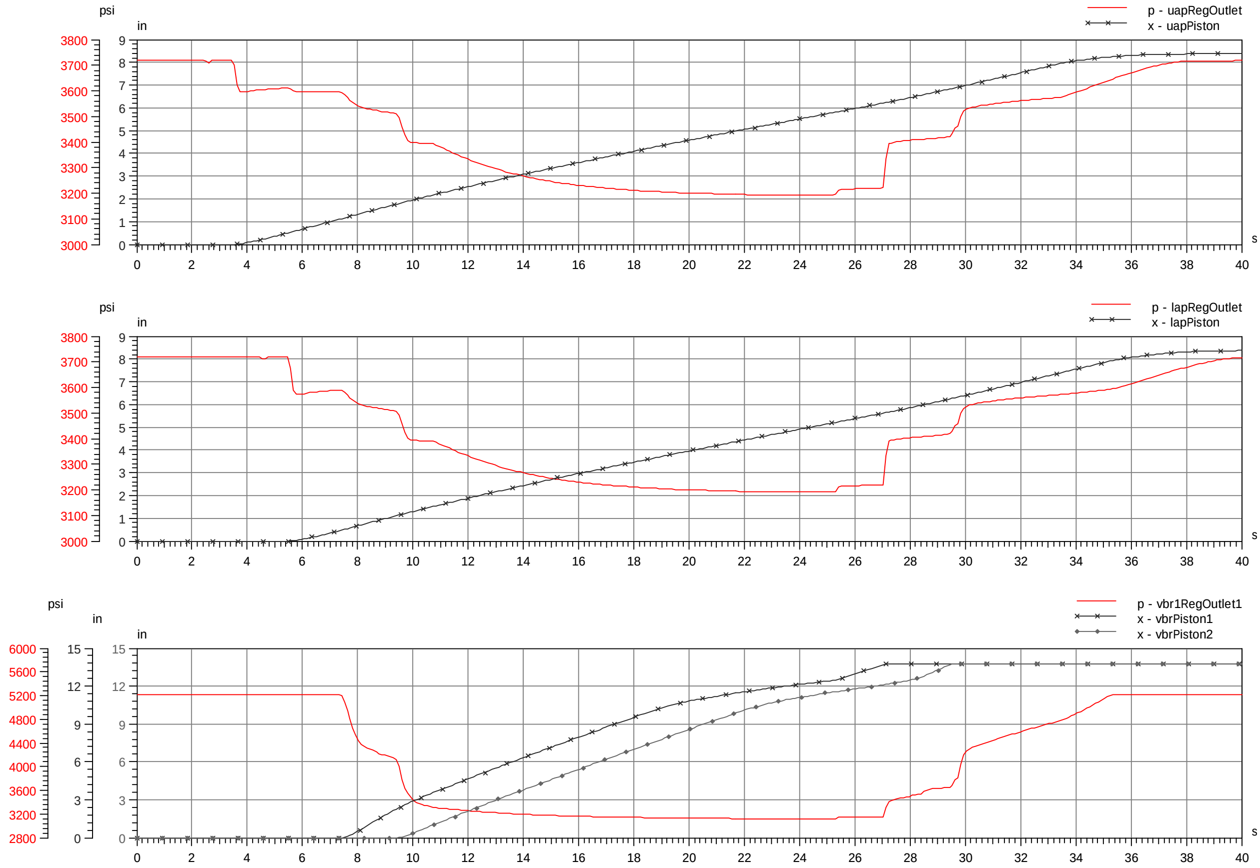


Figure 69) Pressure trends and actuator positions for Case 2-5a

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR1 actuator position	in
x – vbrPiston2	VBR2 actuator position	in

The LMRP accumulator oil volume is initially 115.7 USgal which is 31.7 USgal more than for the system pre-charged according to specifications.

When operating two annular preventers and two VBR's in parallel, the LMRP accumulator oil volume drops to a minimum of 95.3 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 4562 psi (2344 psi + static head).

Minimum pressure is 18 psi lower than for the same system with pre-charge pressure according to specifications.

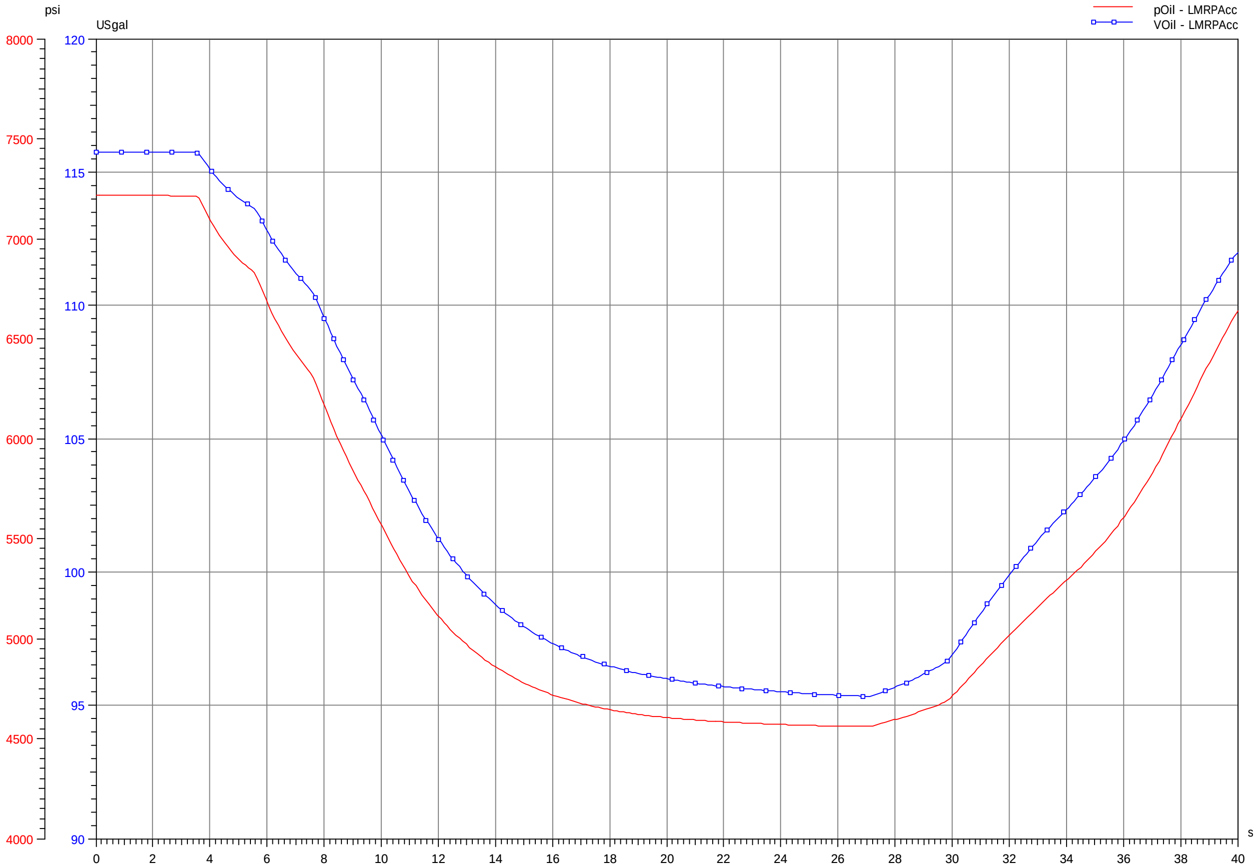


Figure 70) LMRP accumulator pressure and oil volume – Case 2-5a

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 71) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while opening two annular preventer and two VBR's in parallel. As can be seen, the pressure drops below 4200 psi and all three pumps starts. The first pump will start at 12 seconds, the second pump at 16 seconds and the last pump at 20 seconds.

The surface system has only one small difference from case 1-7. The last pump starts one second earlier.

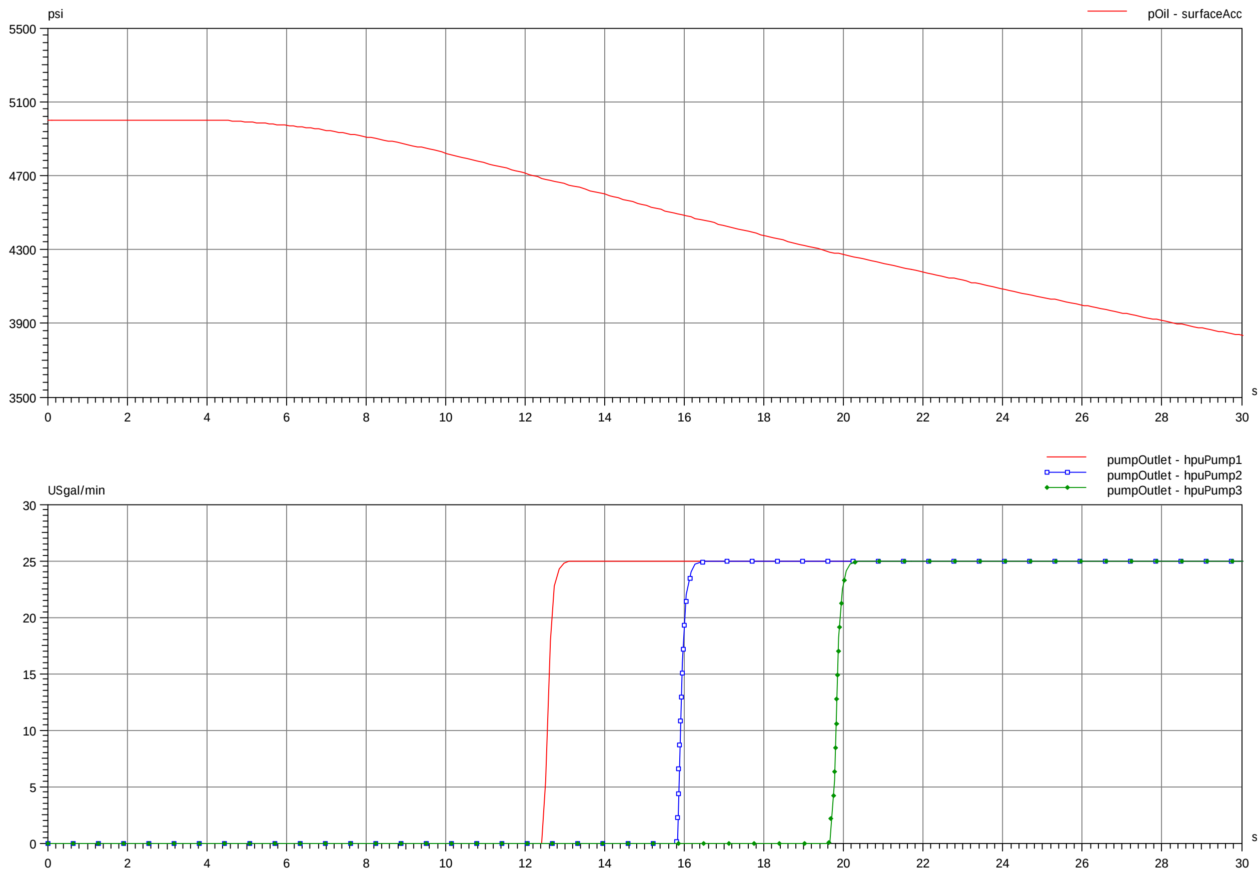


Figure 71) Surface accumulator pressure and pump flows – 2-5a

Legend:	Description	Unit
pOil - surface	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.2.5.2 Case 2-5b: With three out of four LMRP accumulators available

Figure 72) shows the pressure trends and actuator positions for the two annular preventers and the two VBR's. The first annular preventer is “fired” to open at 2 seconds, the second annular at 4 seconds, the first VBR at 6 seconds and the second VBR at 8 seconds. This gives a parallel operation of all four valve actuators.

There is a small difference in the actuator performance compared to the simulations performed for the system with pre-charge pressure according to specifications. The difference is less than a second for the last VBR.

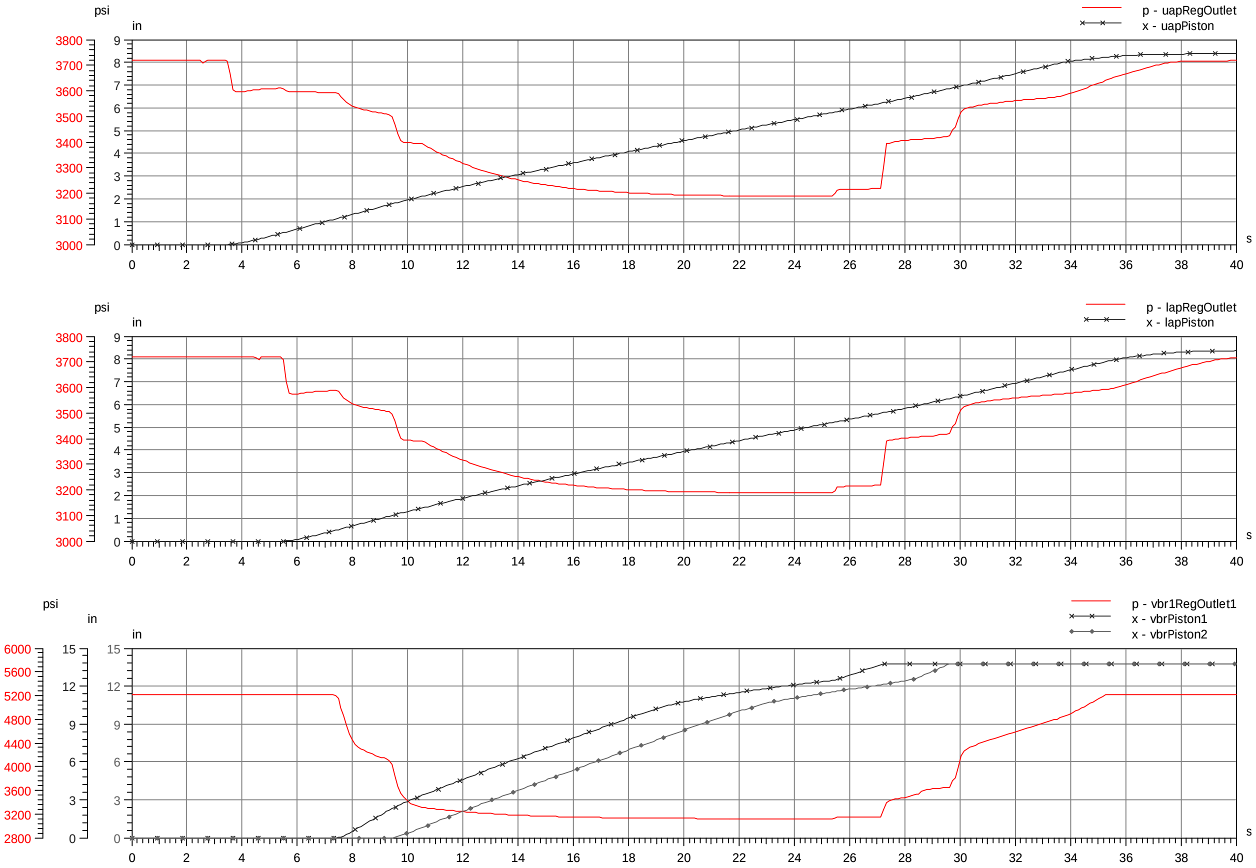


Figure 72) Pressure trends and actuator positions for Case 2-5b

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR1 actuator position	in
x – vbrPiston2	VBR2 actuator position	in

The LMRP accumulator oil volume is initially 63.2 USgal which is 20.8 USgal less than for the same system with all four accumulators available.

When operating two annular preventers and two VBR's in parallel, the LMRP accumulator oil volume drops to a minimum of 43.4 USgal including 1 USgal dead volume. At the same time the supply pressure drops to a minimum of 4556 psi (2338 psi + static head).

Minimum pressure is 24 psi lower than for the same system with all four accumulators available.

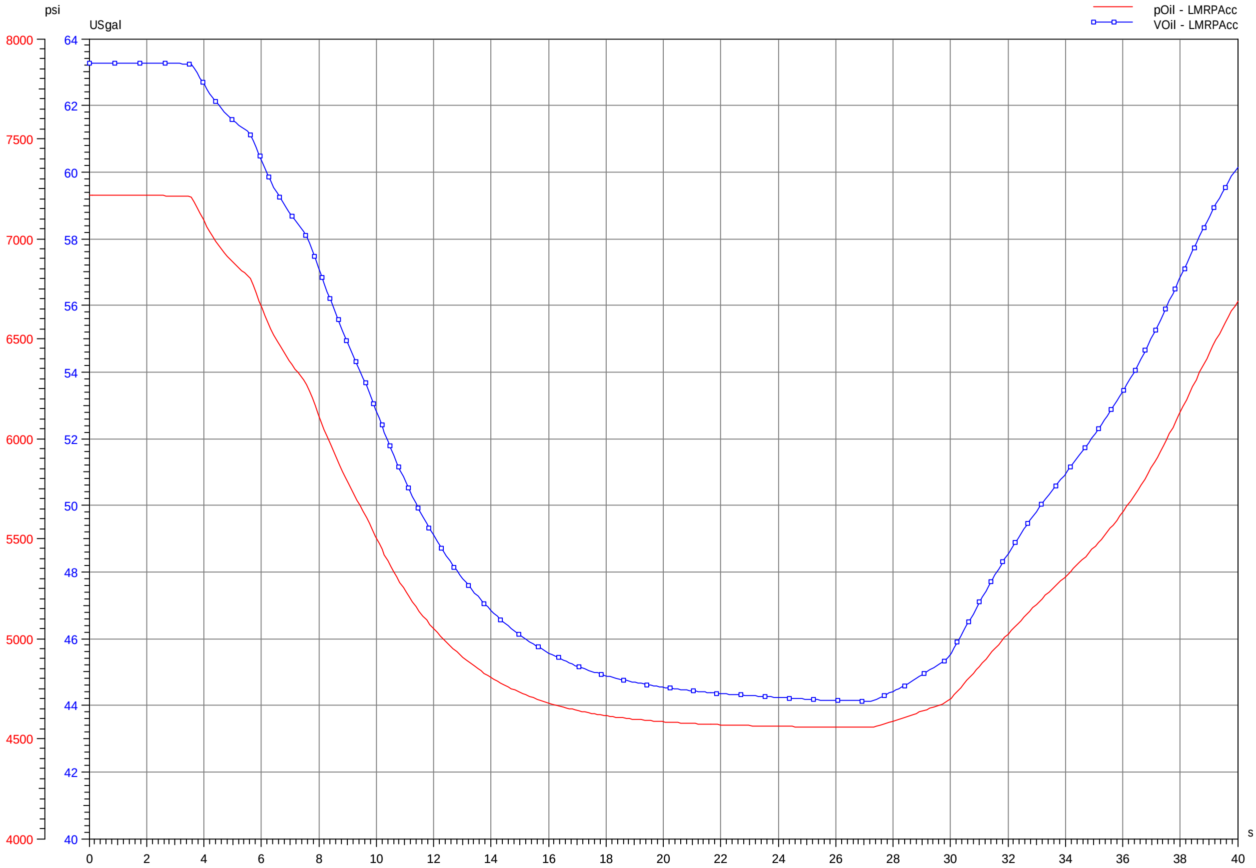


Figure 73) LMRP accumulator pressure and oil volume – Case 2-5b

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

Figure 74) shows the surface accumulator pressure together with the pump flow from the three surface HPU pumps while opening two annular preventer and two VBR in parallel. As can be seen, the pressure drops below 4200 psi and all three pumps starts. The first pump will start at 12 seconds, the second pump at 16 seconds and the last pump at 19 seconds.

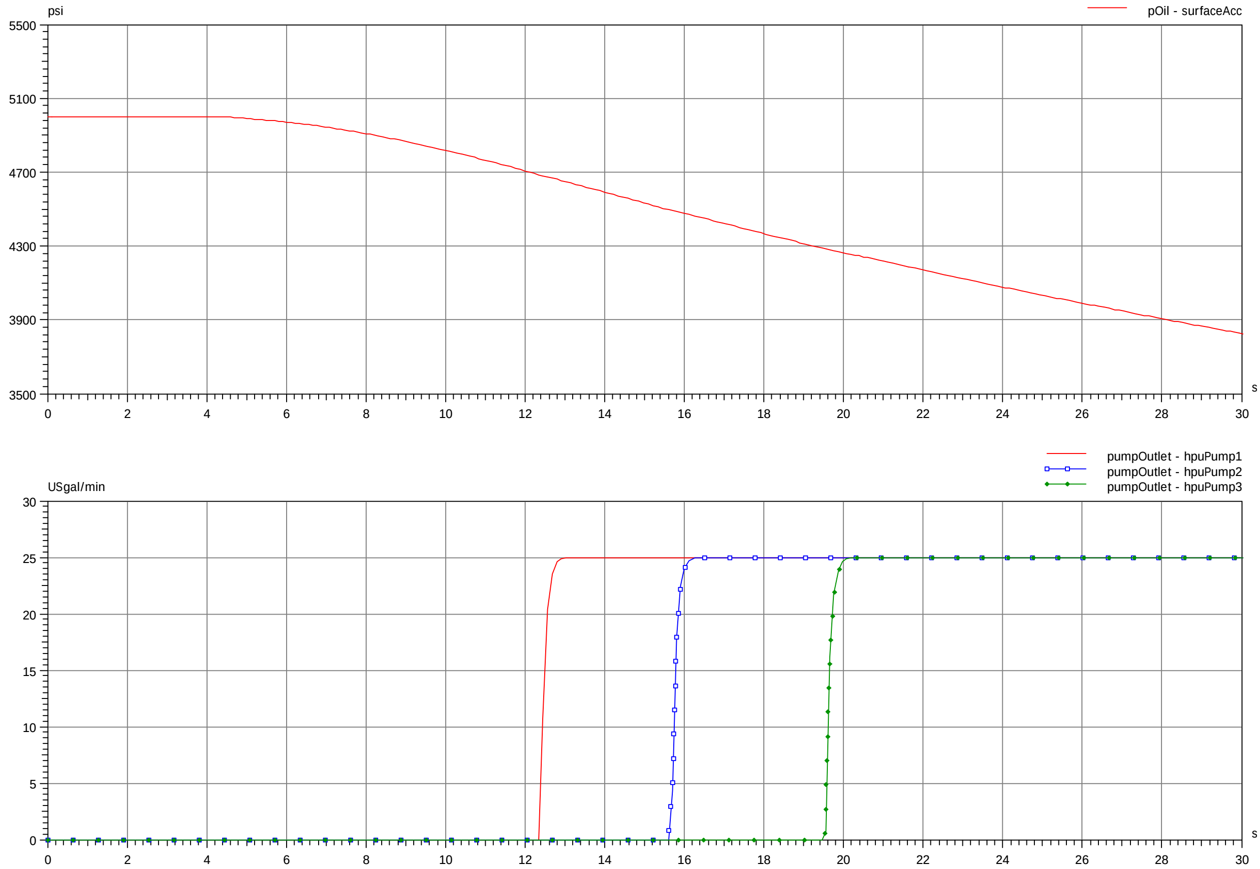


Figure 74) Surface accumulator pressure and pump flows – 2-5b

Legend:	Description	Unit
pOil - surface	Pressure in surface accumulators	psi
pumpOutlet – hpuPump1	Flow from HPU pump 1	USgal/min
pumpOutlet – hpuPump2	Flow from HPU pump 2	USgal/min
pumpOutlet – hpuPump3	Flow from HPU pump 3	USgal/min

5.3 Scenario 3: Operations with high BOP pressure

The scope of this scenario is to replicate the stand pipe pressure seen in Figure 1), section 1.

The scenario has been divided in to 2 separate cases:

Case 3-1: Closing one annular preventer followed by a second annular preventer

Case 3-2: Closing one annular preventer followed by the second annular preventer and one VBR in parallel

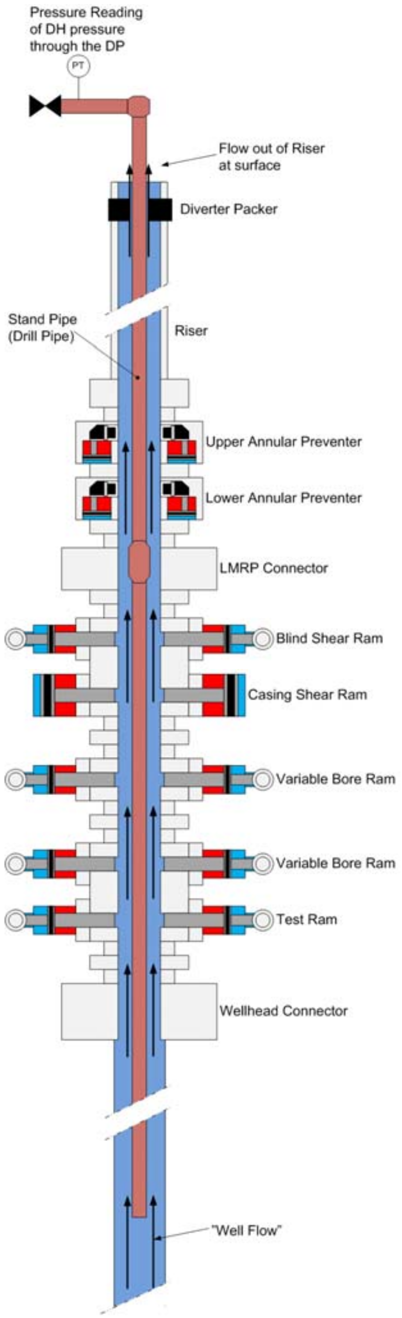


Figure 75) Model of well and riser

To better understand the dynamic effects acting on the annular preventer actuator when closing with a high flow, a simple model of water filled well is modelled. The figure to left show a sketch of the modelled well and riser.

The model is set up with 1900 USgal flow from the well and up the riser and the drill pipe.

The simulations start at steady conditions. The flow is then ramped up from 0 to 1900 USgal/min from 0 to 1 minute.

After 2 minutes, the surface valve on top of the drill pipe is closed and the flow through the drill pipe stops. The pressure logged on top of the drill pipe reflects the well pressure minus static head when the flow through the drill pipe is zero.

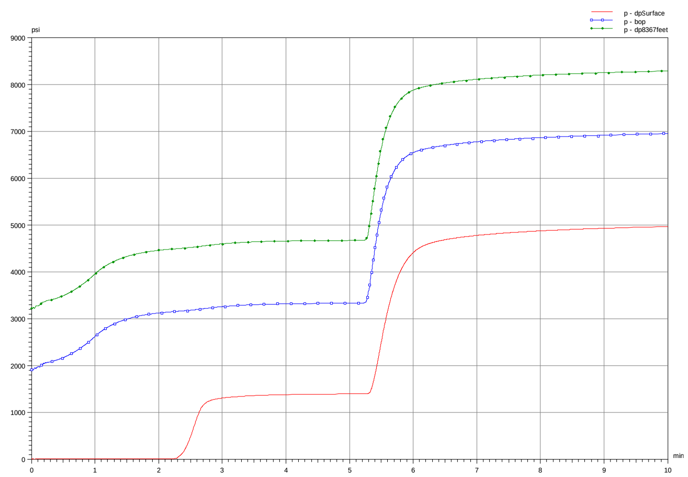


Figure 76) Pressure trend in well model

The figure above shows the pressure trend in the simplified well modelled when an annular preventer is closed at 5 minutes.

5.3.1 Case 3-1: Closing UAP and LAP in series

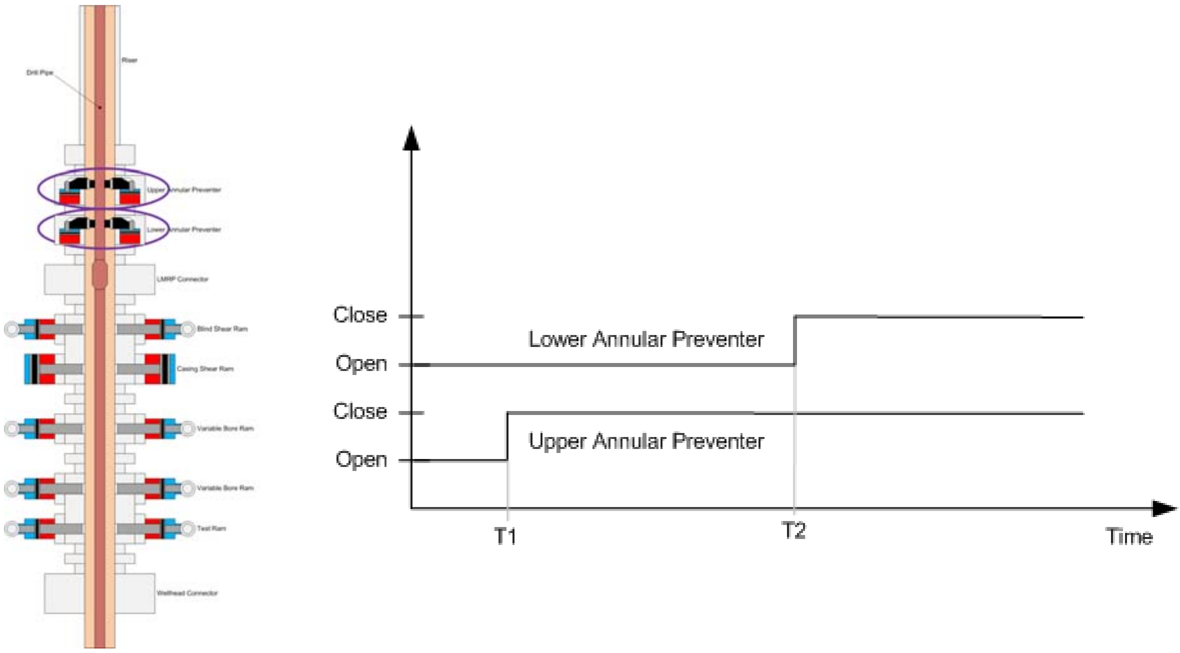


Figure 77) Valve Operation Scheme for Case 3-1

Figure 77) shows the operation of the BOP valves.

Ident.	Time [min]	Action
T1	5	UAP is “fired” to close
T2	14	LAP is “fired” to close

The time from zero to the first valve closure is used to get steady flow conditions in the well model. The time difference between the two valve operations is estimated from the stand pipe pressure measurements in Figure 1), section 1.

The simplified well model is set up with a flow of 1900 USgal/min, maximum flowing pressure of 11500 psi and maximum shut-in pressure of 11.825 psi measured at Stand Pipe down-hole end.

Figure 78) shows the pressure trends and actuator positions for the two annular preventers.

As can be seen, the first annular preventer close and compress the “packer” element before it retracts 0.3 inches from the drill pipe wall. The time period for the retraction corresponds with the pressure build up in the BOP seen in the next plot - Figure 79).

The annular preventer and its internal components are modelled based on general arrangement drawings and assumptions. It is set up to close around the pipe at 8.03 inches. The simulations show that the packer elements retract and flow can pass the two packer elements. Exact distance for actuator travel depends on the actuator and packer bahaviour, however, the simulations show that the annular preventers most likely not seals with a closing pressure of 1500 psi under these conditions.

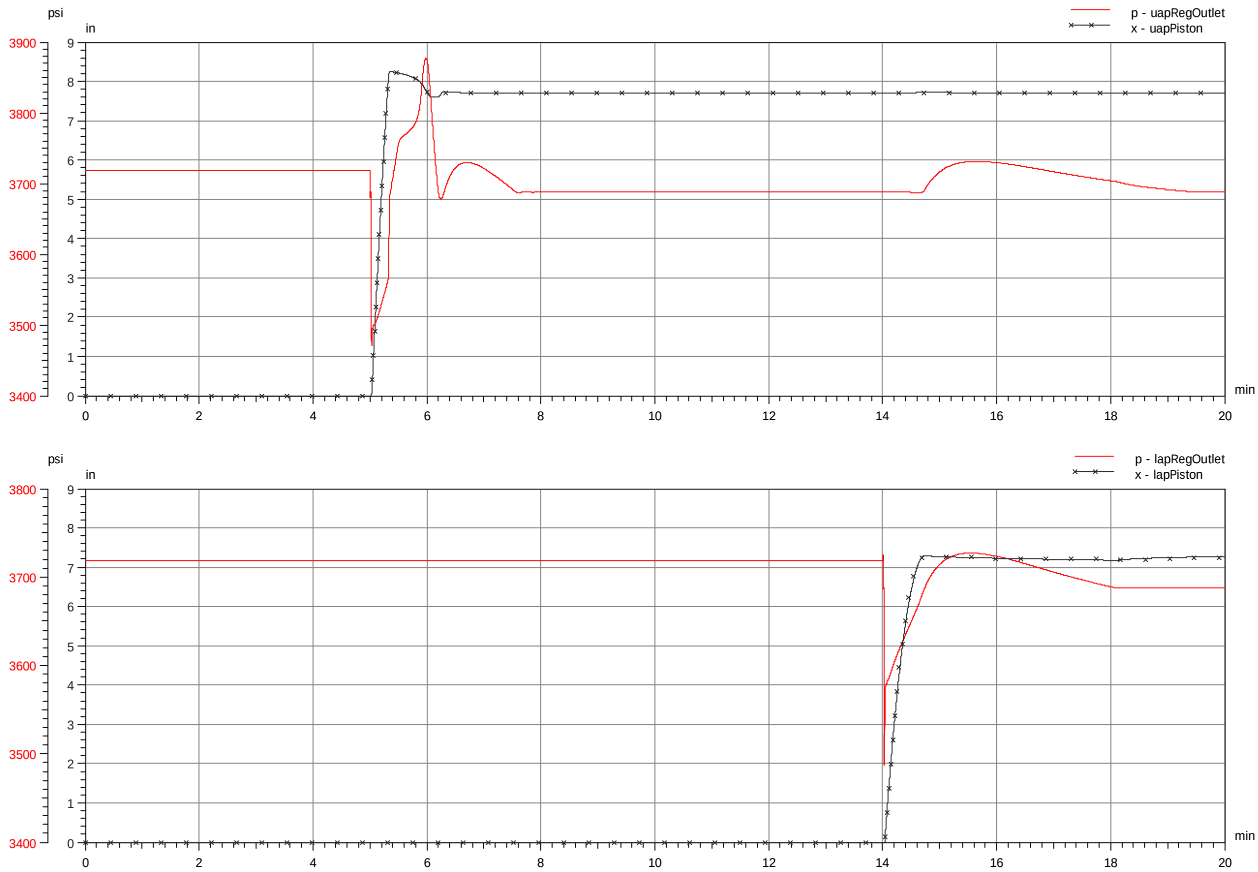


Figure 78) Pressure trends and actuator positions for Case 3-1

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in

The pressure trend from the simplified well model can be seen in Figure 79). It gives a pressure build up which is close to the pressure behaviour in the real well. It also reflects the delay between BOP pressure and the logged stand pipe pressure on surface.

Note that the BOP pressure is measured between the annular preventers and the variable bore rams.

From this pressure log, it is not likely that closing one annular preventer with 1500 psi combined with a high BOP pressure starts to open the preventer again as seen in Figure 1) between 21:36 and 21:42. It retracts approx. 0.3 inches and stabilizes the well flow and pressure conditions in this point.

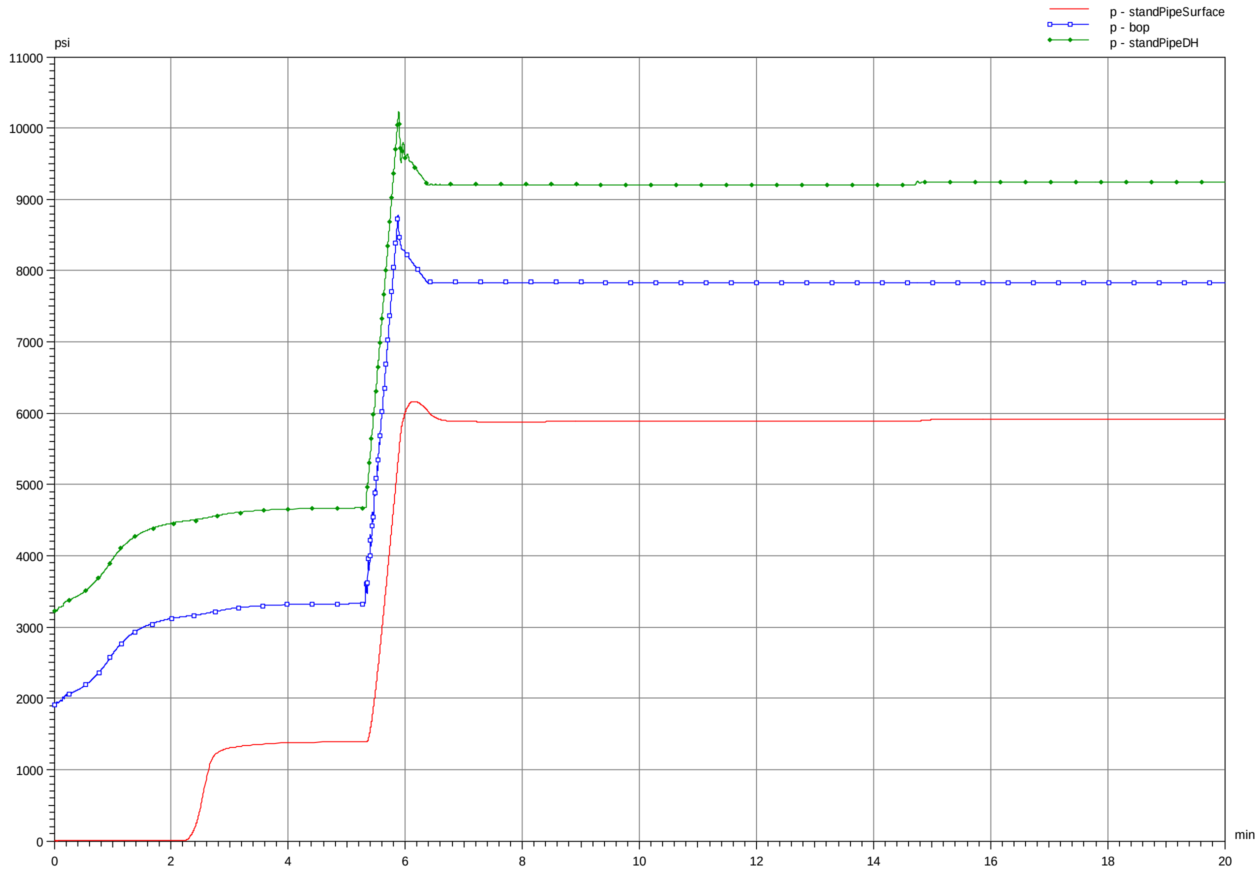


Figure 79) Pressure trends in simplified well model Case 3-1

Legend:	Description	Unit
p – standpipeSurface	Surface Stand Pipe pressure	psi
p – bop	Pressure in BOP	psi
p – standPipeDH	Down Hole Stand Pipe pressure	psi

5.3.2 Case 3-2: Closing UAP followed by LAP and one VBR in parallel

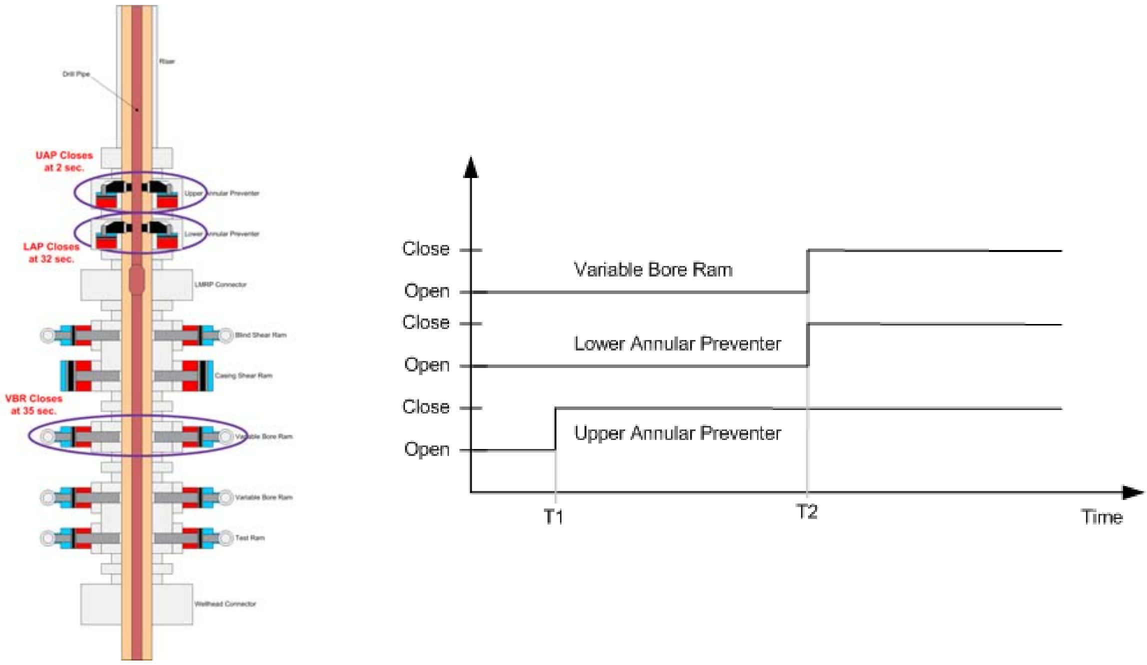


Figure 80) Valve Operation Scheme for Case 3-2

Figure 80) shows the operation of the BOP valves.

Ident.	Time [min]	Action
T1	5	UAP is “fired” to close
T2	14	LAP is “fired” to close together with one VBR

The time from zero to the first valve closure is used to get steady flow conditions in the well model. The time difference between the two valve operations is estimated from the stand pipe pressure measurements in Figure 1), section 1.

The simplified well model is set up with a flow of 1900 USgal/min, maximum flowing pressure of 11500 psi and maximum shut-in pressure of 11.825 psi measured at Stand Pipe down-hole end.

Figure 81) shows the pressure trends and actuator positions for the two annular preventers.

As can be seen, the first annular preventer close and compress the “packer” element before it retracts 0.3 inches from the drill pipe wall. The time period for this retraction corresponds with the pressure build up in the BOP seen in the next plot - Figure 82).

The annular preventer and its internal components are modelled based on general arrangement drawings and assumptions. The model is set up to close around the pipe at 8.03 inches. The simulations show that the packer elements retract and flow can pass the two packer elements. Exact distance for actuator travel depends on the actuator and packer internal. However, the simulations show that the annular preventers most likely not seals with a closing pressure of 1500 psi under these conditions but that the VBR will close without any restrictions.

The position plot of the upper annular preventer does not show any signs of further retracting when the lower annular preventer closes.

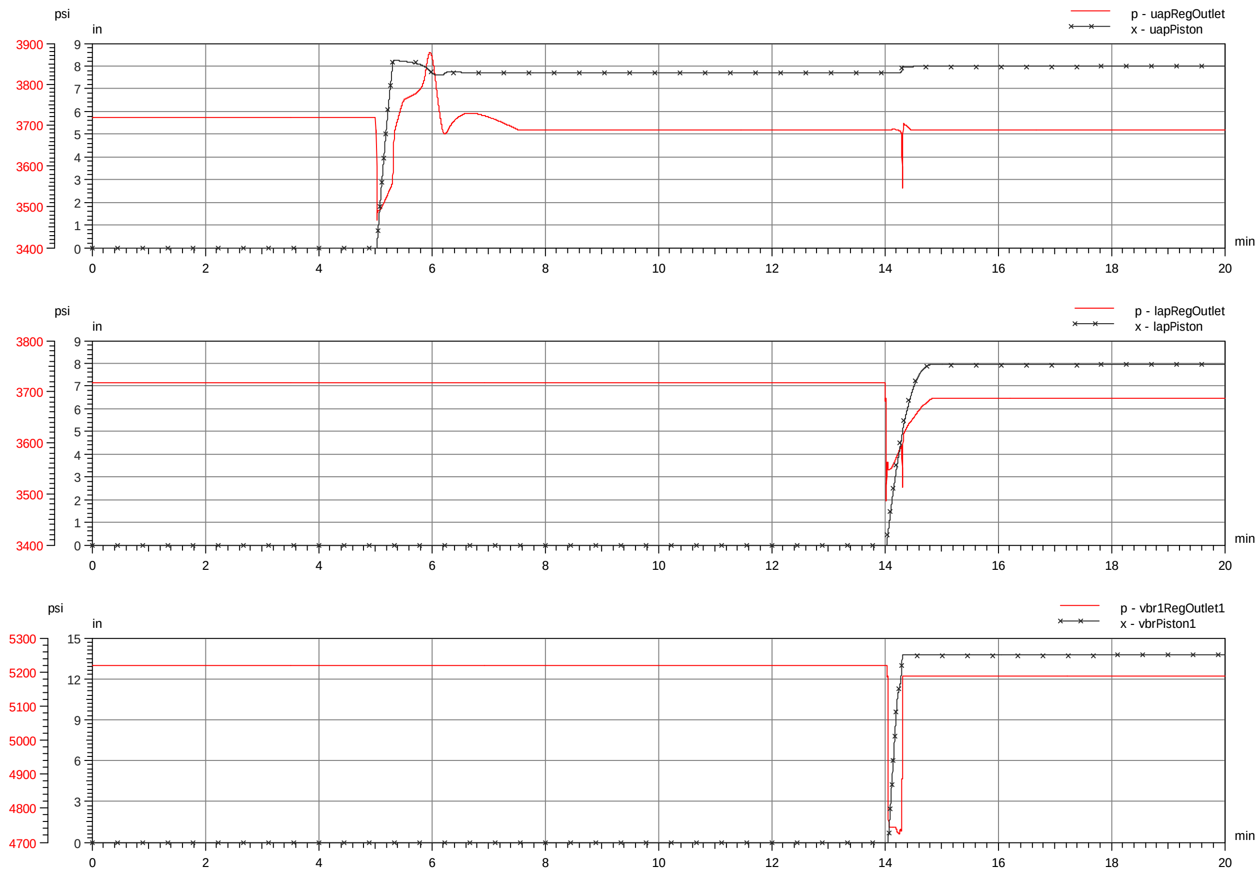


Figure 81) Pressure trends and actuator positions for Case 3-2

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the ram pressure regulator	psi
x – vgr1Piston1	VBR1 actuator position	in

The pressure trend from the simplified well model can be seen in Figure 82). It gives a pressure build up which is close to the pressure behaviour in the real well. It also reflects the delay between BOP pressure and the logged stand pipe pressure on surface.

Note that the BOP pressure is measured between the annular preventers and the variable bore rams and does not reflects the BOP pressure below the VBR after closing.

From this pressure log, it is not likely that closing one annular preventer with 1500 psi combined with a high BOP pressure starts to open the preventer again as seen in Figure 1) between 21:36 and 21:42. However it also shows that when the VBR closes, the stand pipe pressure increases fast as in the end of the pressure plot in Figure 1).

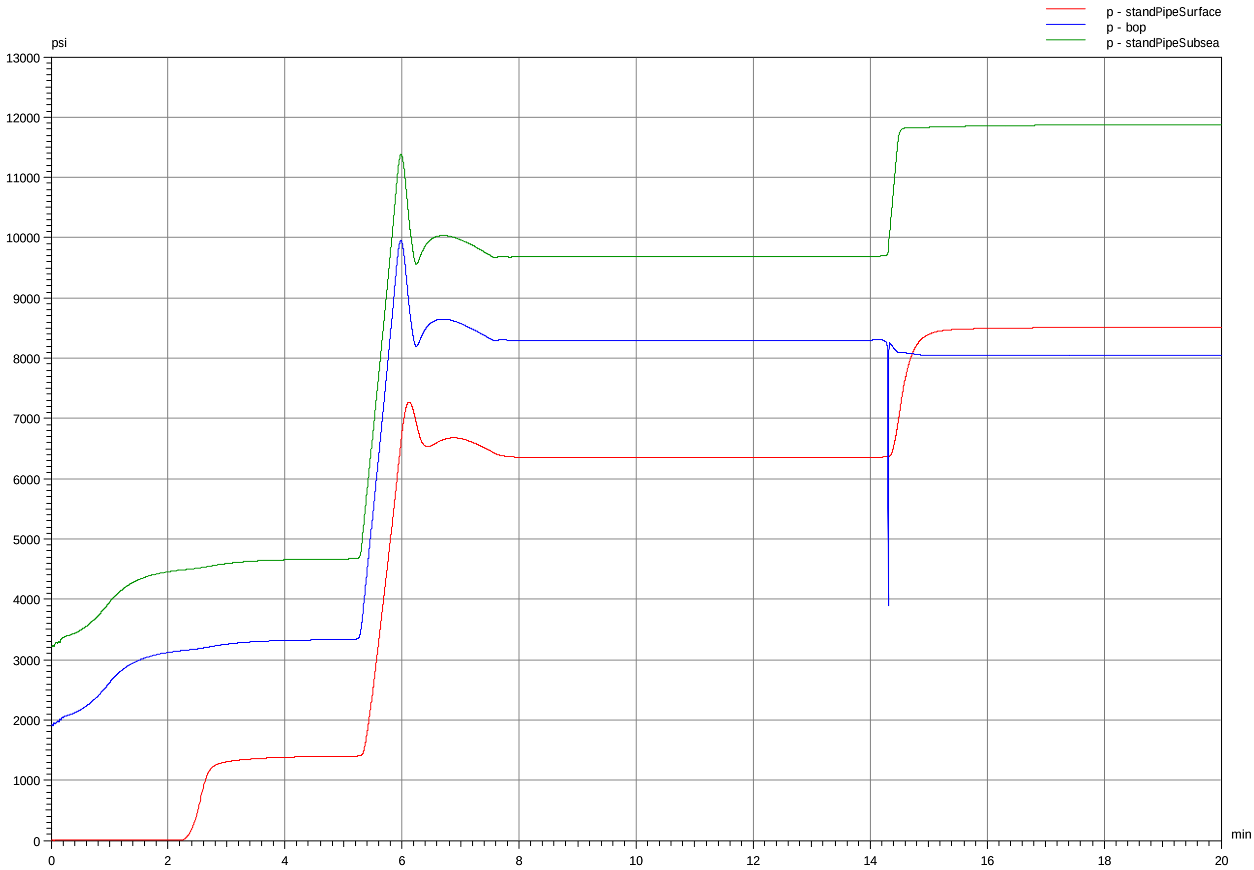


Figure 82) Pressure trends in simplified well model Case 3-2

Legend:	Description	Unit
p – standpipeSurface	Surface Stand Pipe pressure	psi
p – bop	Pressure in BOP	psi
p – standPipeDH	Down Hole Stand Pipe pressure	psi

5.4 Scenario 4: Leakage in the hydraulic system

The scope of this scenario is to replicate the stand pipe pressure seen in Figure 1).

The scenario has been divided in to 2 cases:

Case 4-1: Closing one annular preventer followed by a second annular preventer

Case 4-2: Closing one annular preventer followed by the second annular preventer and one VBR in parallel

Each of the two cases shall be simulated with the two following leak rates a) 75 USgal @ 1500 psi dp and b) 100 USgal @ 1500 psi dp.

The leakage is modelled in to the annular preventer model as shown in Figure 83). The leakage is included in the T-junction and it bleeds directly to sea.

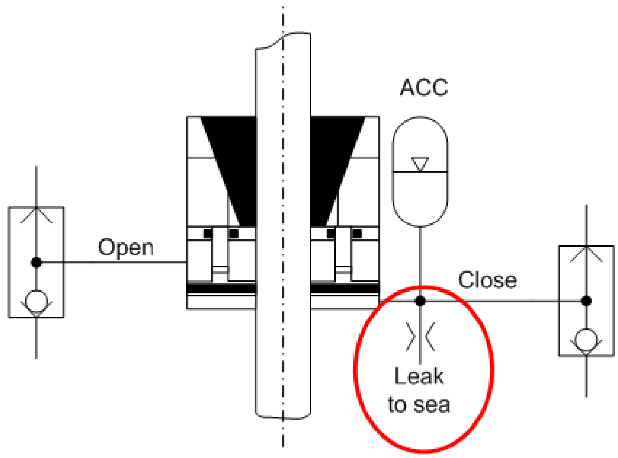


Figure 83) Leakage in annular preventer accumulator connection

5.4.1 Case 4-1: Closing UAP and LAP in series with control line leakage

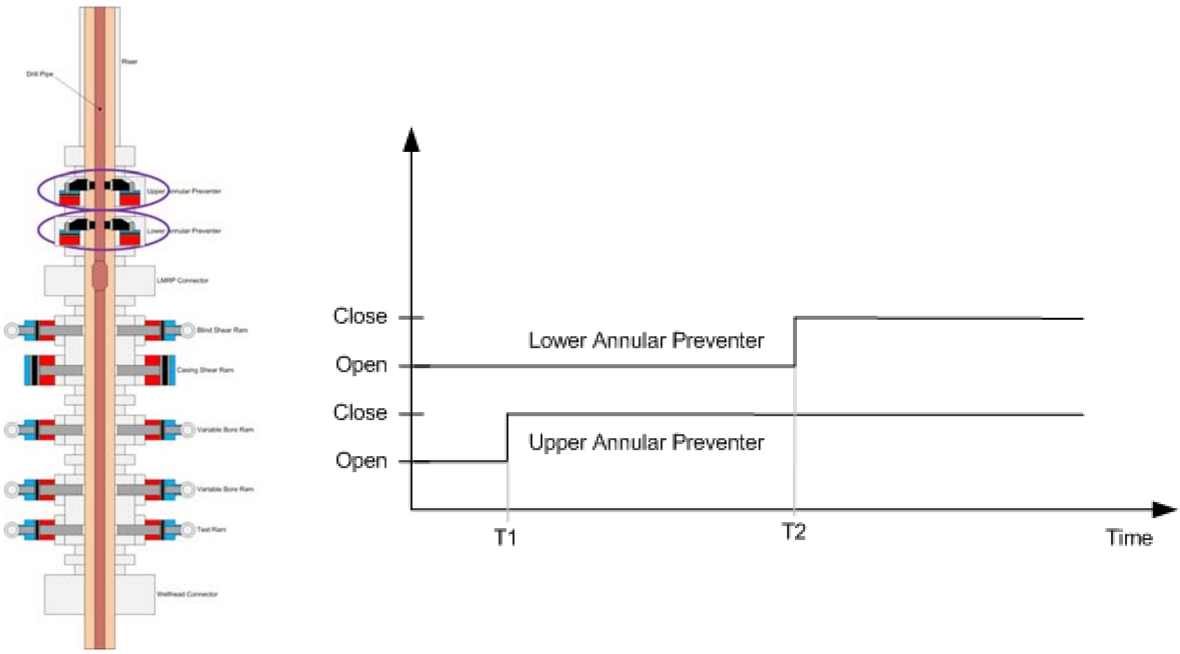


Figure 84) Valve Operation Scheme for Case 4-1a

Figure 84) shows the operation of the BOP valves.

Ident.	Time [min]	Action
T1	5	UAP is “fired” to close
T2	14	LAP is “fired” to close

The time from zero to the first valve closure is used to get steady flow conditions in the well model. The time difference between the two valve operations is estimated from the stand pipe pressure measurements in Figure 1), section 1.

The simplified well model is set up with a flow of 1900 USgal/min, maximum flowing pressure of 11500 psi and maximum shut-in pressure of 11.825 psi measured at DH Stand Pipe end.

5.4.1.1 Case 4-1a: Leak rate of 75 USgal/min

Figure 85) shows the pressure trends and actuator positions for the two annular preventers.

As can be seen, the first annular preventer close and compress the “packer” element before it retracts 0.3 inches from the drill pipe wall. The time period of this retraction corresponds with the pressure build up in the BOP seen in the next plot - Figure 86).

The annular preventer and its internal components are modelled based on general arrangement drawings and assumptions. The model is set up to close around the pipe at 8.03 inches. The simulations show that the packer elements retract and flow can pass the two packer elements. Exact distance for actuator travel depends on the actuator and packer internal. However, the simulations show that the annular preventers most likely not seals with a closing pressure of 1500 psi under these conditions.

The position plot of the upper annular preventer does not show any signs of retracting when the lower annular preventer closes.

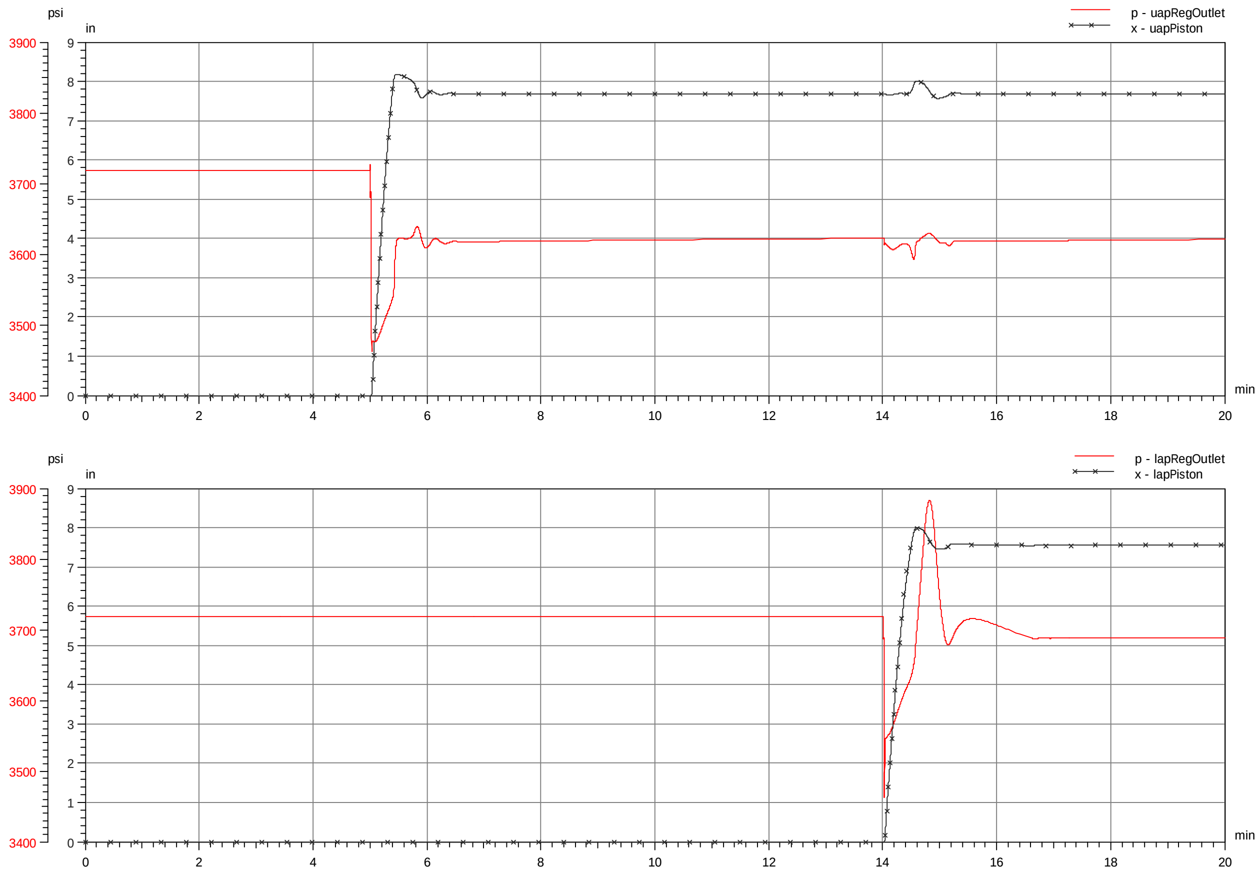


Figure 85) Pressure trends and actuator positions for Case 4-1a

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in

The pressure trend from the simplified well model can be seen in Figure 86). It gives a pressure build up which is close to the pressure behaviour in the real well. It also reflects the delay between BOP pressure and the logged stand pipe pressure on surface.

Note that the BOP pressure is measured between the annular preventers and the variable bore rams and does not reflects the real BOP pressure after the VBR's are closed.

From this pressure log, it is not likely that closing one annular preventer with 1500 psi combined with a high BOP pressure starts to open the preventer again as seen in Figure 1) between 21:36 and 21:42.

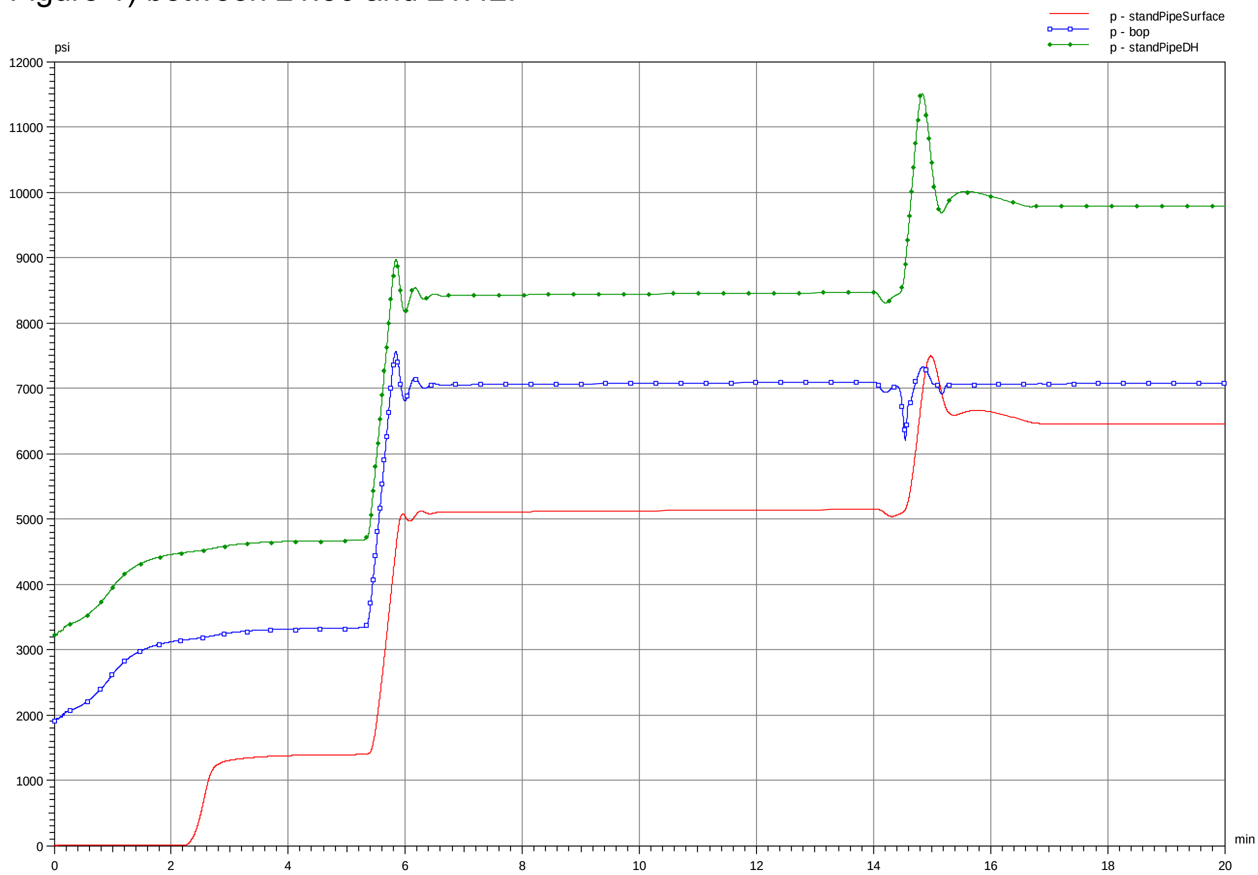


Figure 86) Pressure trends in simplified well model Case 4-1a

Legend:	Description	Unit
p – standpipeSurface	Surface Stand Pipe pressure	psi
p – bop	Pressure in BOP	psi
p – standPipeDH	Down Hole Stand Pipe pressure	psi

5.4.1.2 Case 4-1b: Leak rate of 100 USgal/min

Figure 87) shows the pressure trends and actuator positions for the two annular preventers.

As can be seen, the first annular preventer close and compress the “packer” element before it retracts 0.3 inches from the drill pipe wall. The time period for this retraction corresponds with the pressure build up in the BOP seen in the next plot - Figure 88).

The annular preventer and its internal components are modelled based on general arrangement drawings and assumptions. The model is set up to close around the pipe at 8.03 inches. The simulations show that the packer elements retract and flow can pass the two packer elements. Exact distance for actuator travel depends on the actuator and packer internal. However, the simulations show that the annular preventers most likely not seals with a closing pressure of 1500 psi under these conditions.

The position plot of the upper annular preventer does not show any signs of retracting when the lower annular preventer closes.

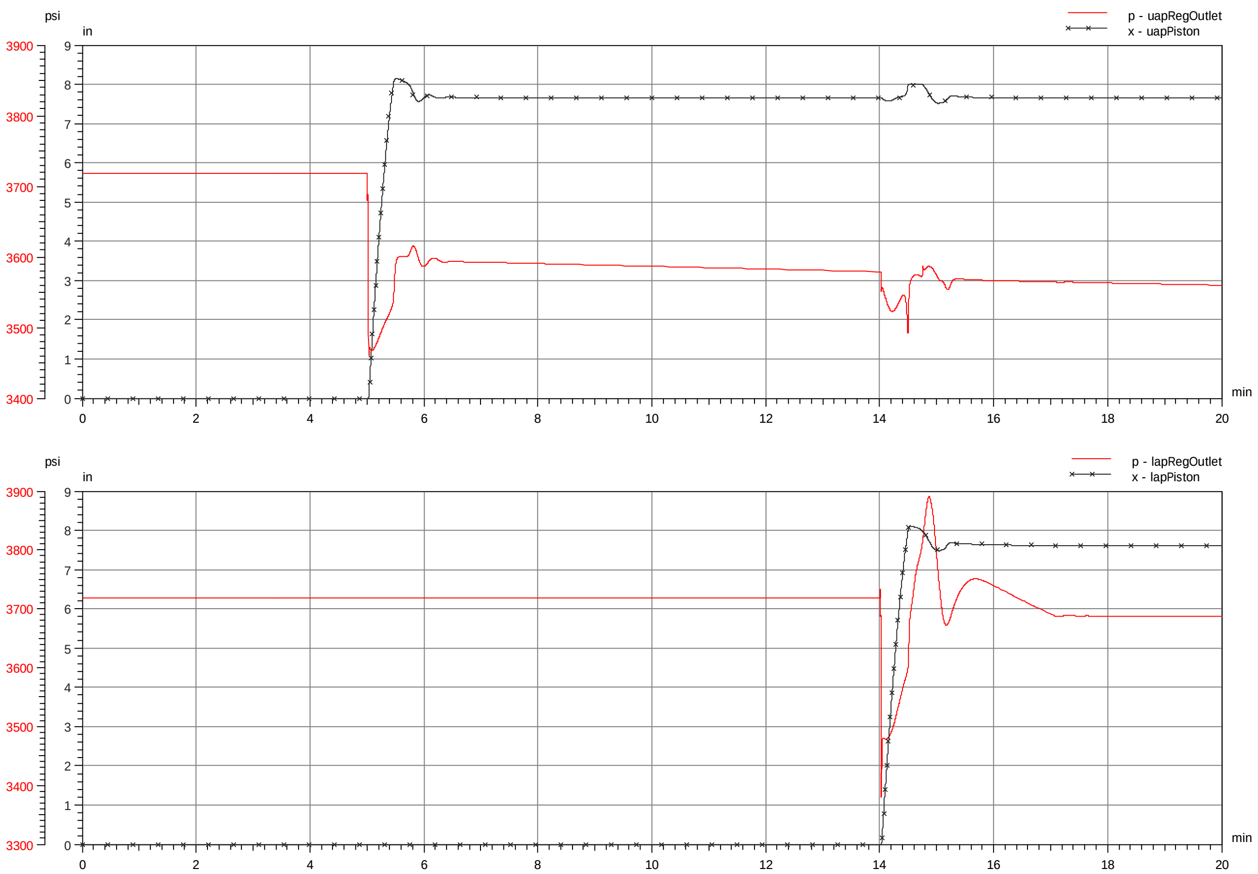


Figure 87) Pressure trends and actuator positions for Case 4-1b

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in

The pressure trend from the simplified well model can be seen in Figure 88). It gives a pressure build up which is close to the pressure behaviour in the real well. It also reflects the delay between BOP pressure and the logged stand pipe pressure on surface.

Note that the BOP pressure is measured between the annular preventers and the variable bore rams and do not reflects real BOP pressure after closing the VBR.

From this pressure log, it is not likely that closing one annular preventer with 1500 psi combined with a high BOP pressure starts to open the preventer again as seen in Figure 1) between 21:36 and 21:42.

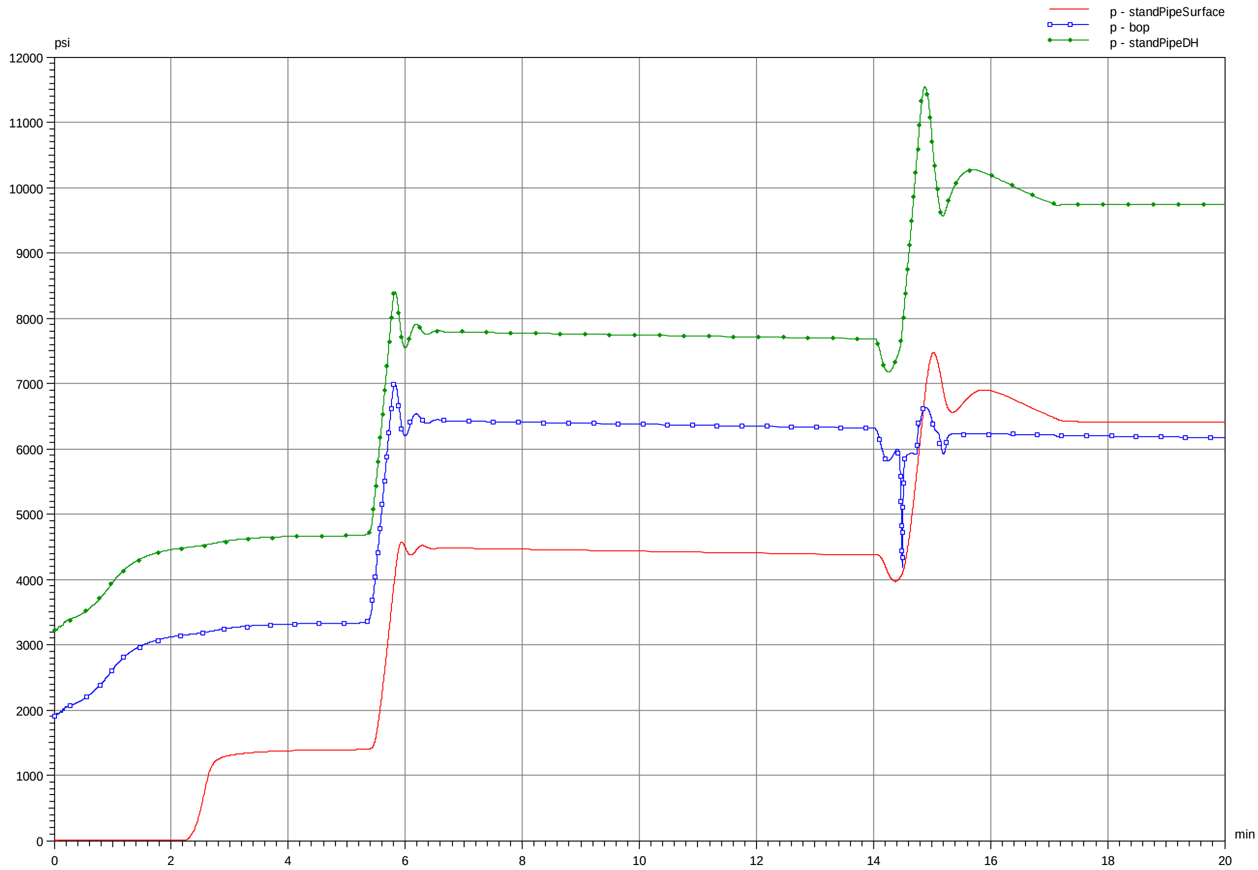


Figure 88) Pressure trends in simplified well model Case 4-1b

Legend:	Description	Unit
p – standpipeSurface	Surface Stand Pipe pressure	psi
p – bop	Pressure in BOP	psi
p – standPipeDH	Down Hole Stand Pipe pressure	psi

Figure 89) shows the LMRP accumulator pressure and volume. Since the leak rate is higher than the pump capacity, the leakage in the end will empty the supply accumulator system. At this point, the preventers will start to open.

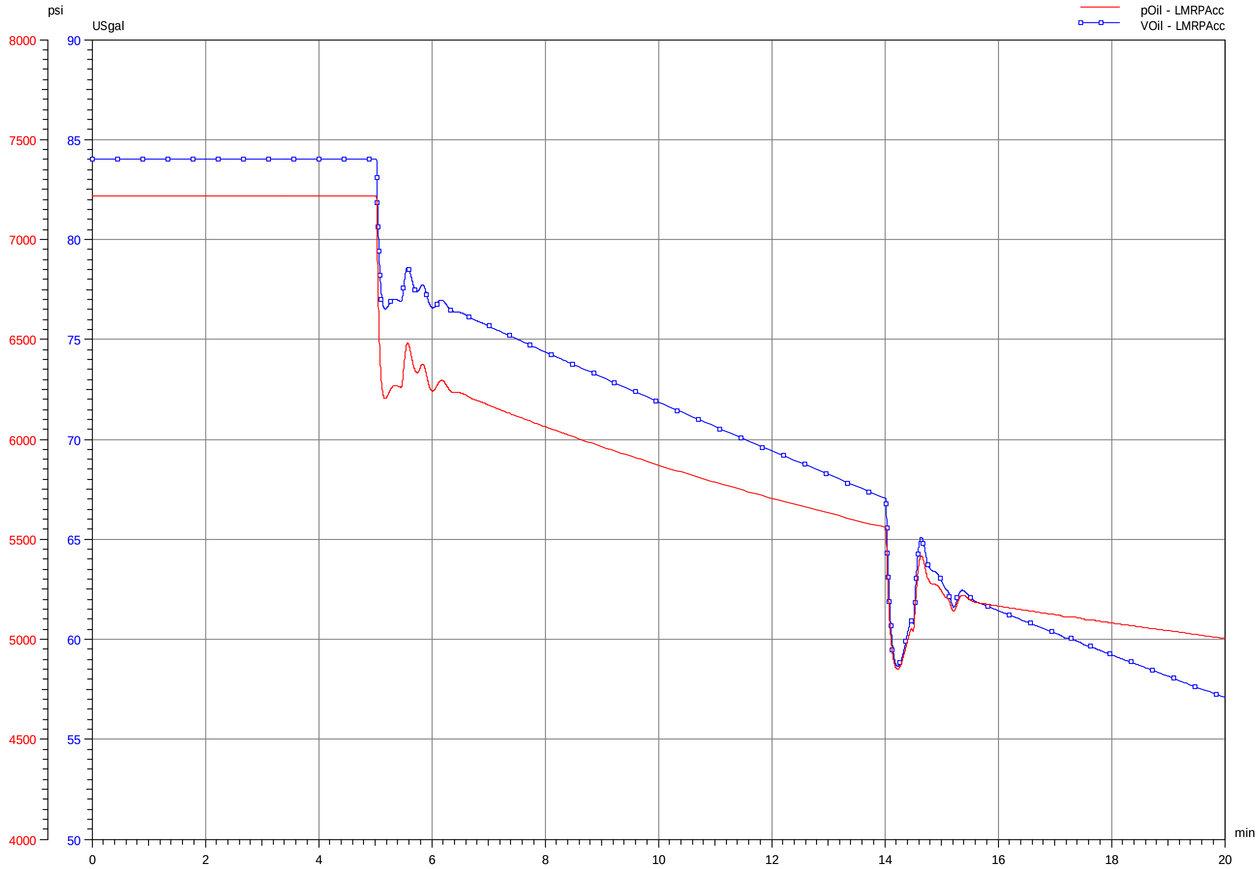


Figure 89) LMRP accumulator pressure and oil volume – Case 4-1b

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

5.4.2 Case 4-2: Closing UAP followed by LAP and one VBR in parallel

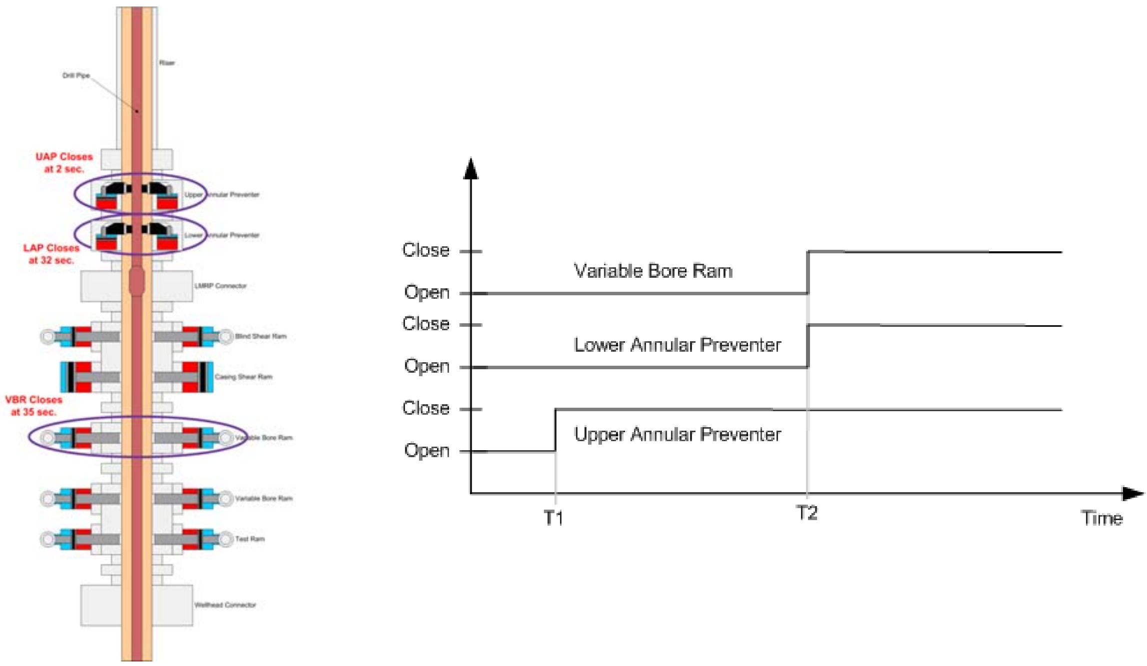


Figure 90) Valve Operation Scheme for Case 4-2

Figure 90) shows the operation of the BOP valves.

Ident.	Time [min]	Action
T1	5	UAP is “fired” to close
T2	14	LAP is “fired” to close in parallel with one VBR

The time from zero to the first valve closure is used to get steady conditions in the well model. The time difference between the two valve operations is estimated from the stand pipe pressure measurements in Figure 1), section 1.

The simplified well model is set up with a flow of 1900 USgal/min, maximum flowing pressure of 11500 psi and maximum shut-in pressure of 11.825 psi measured at down-hole Stand Pipe end.

5.4.2.1 Case 4-2a: Leak rate of 75 USgal/min

Figure 91) shows the pressure trends and actuator positions for the two annular preventers.
As can be seen, the first annular preventer close and compress the “packer” element before it retracts 0.3 inches from the drill pipe wall. The time period for this retraction corresponds with the pressure build up in the BOP seen in the next plot - Figure 92).

The annular preventer and its internal components are modelled based on general arrangement drawings assumptions. The model is set up to close around the pipe at 8.03 inches. The simulations show that the packer elements retract and flow can pass the two packer elements. Exact distance for actuator travel depends on the actuator and packer internal. However, the simulations show that the annular preventers most likely not seals with a closing pressure of 1500 psi under these conditions but that the VBR will close without any restrictions.

The position plot of the upper annular preventer does not show any signs of retracting when the lower annular preventer opens.

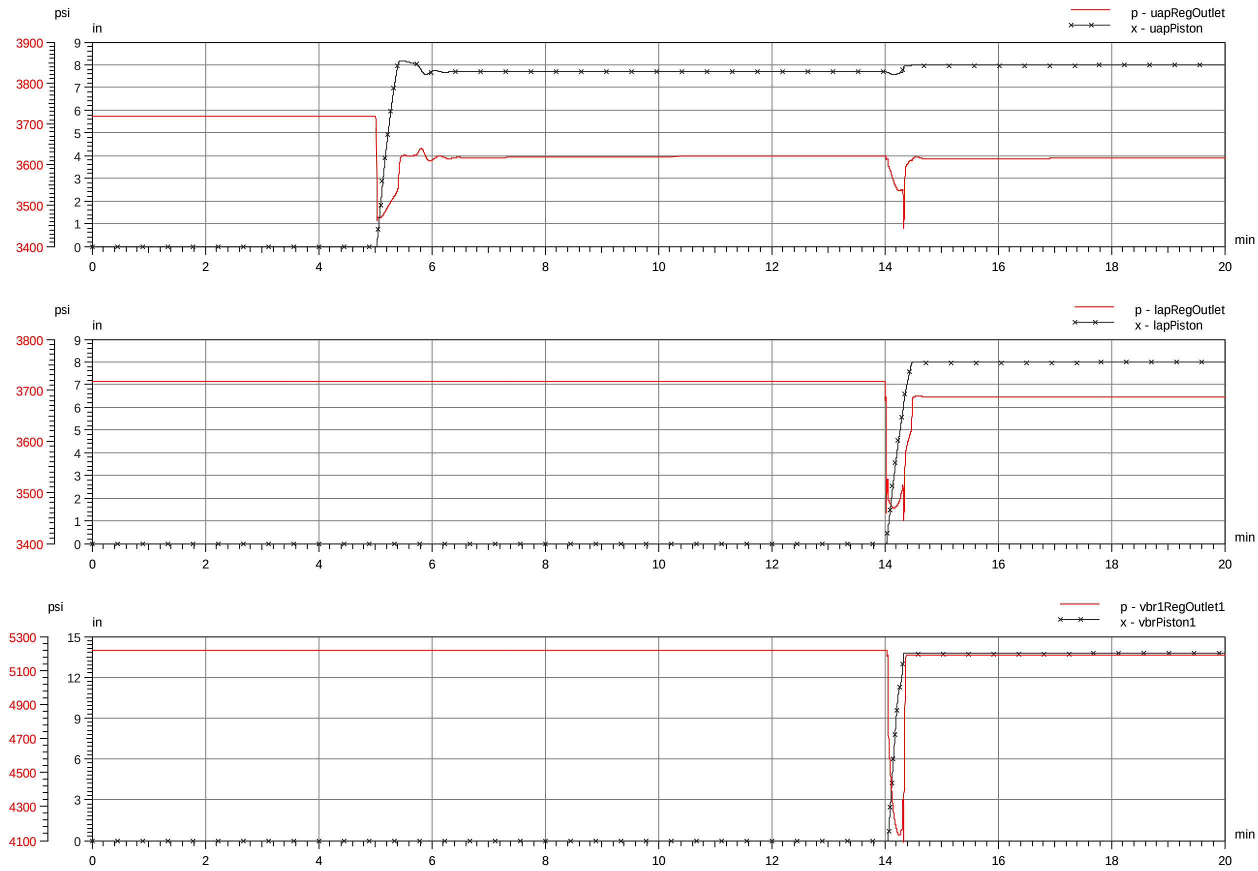


Figure 91) Pressure trends and actuator positions for Case 4-2a

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR actuator position	in

The pressure trend from the simplified well model can be seen in Figure 92) It gives a pressure build up which is close to the pressure behaviour in the real well. It also reflects the delay between BOP pressure and the logged stand pipe pressure on surface.

From this pressure log, it is not likely that closing one annular preventer with 1500 psi combined with a high BOP pressure starts to open the preventer again as seen in Figure 1) between 21:36 and 21:42. However it also shows that when the VBR closes, the stand pipe pressure increases fast as in the end of the pressure plot in Figure 1).

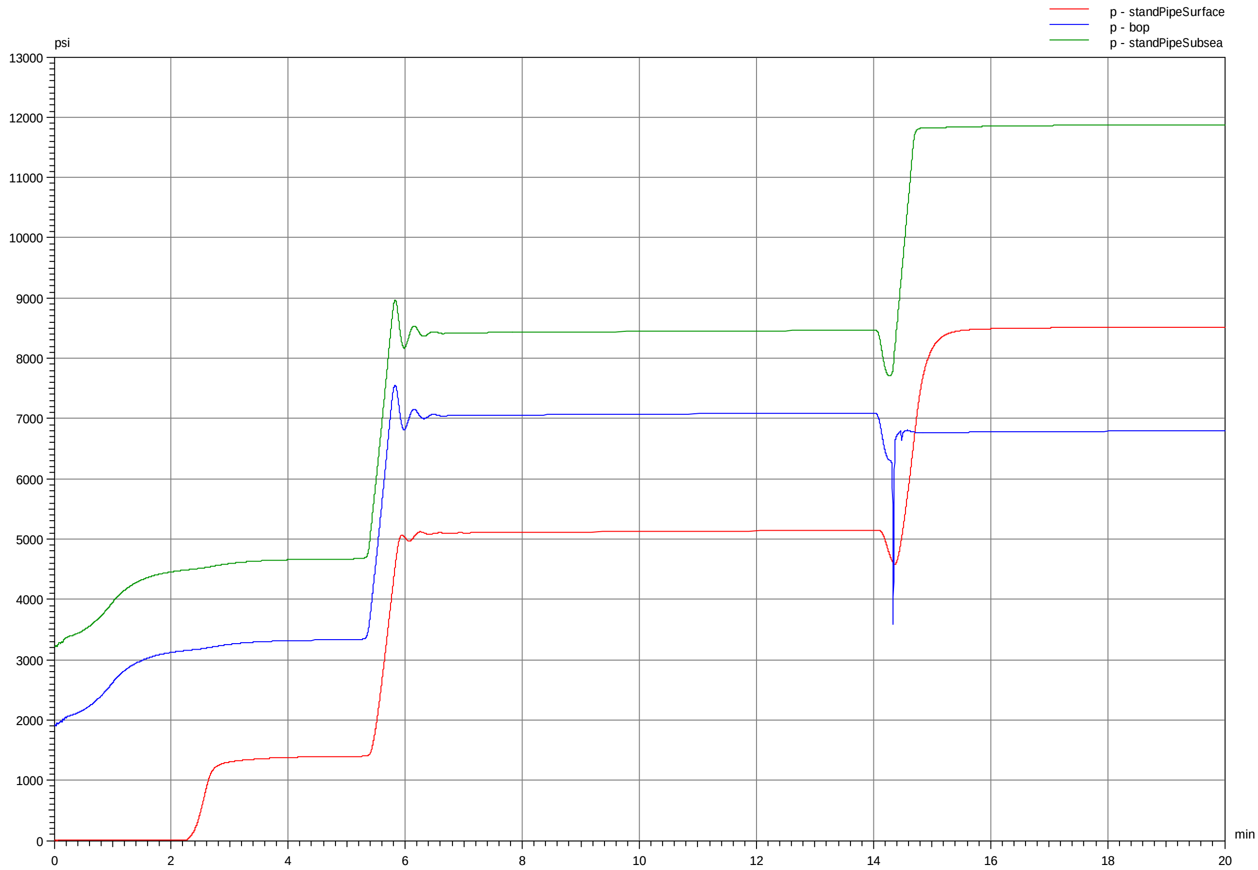


Figure 92) Pressure trends in simplified well model Case 4-2a

Legend:	Description	Unit
p – standpipeSurface	Surface Stand Pipe pressure	psi
p – bop	Pressure in BOP	psi
p – standPipeDH	Down Hole Stand Pipe pressure	psi

5.4.2.2 Case 4-2b: Leak rate of 100 USgal/min

Figure 93) shows the pressure trends and actuator positions for the two annular preventers.
As can be seen, the first annular preventer close and compress the “packer” element before it retracts 0.3 inches from the drill pipe wall. This retraction corresponds with the pressure build up in the BOP seen in the next plot - Figure 94).

The annular preventer and its internal components are modelled based on general arrangement drawings and assumptions. The model is set up to close around the pipe at 8.03 inches. The simulations show that the packer elements retract and flow can pass the two packer elements. Exact distance for actuator travel depends on the actuator and packer internal. However, the simulations show that the annular preventers most likely not seals with a closing pressure of 1500 psi under these conditions but that the VBR will close without any restrictions.

The position plot of the upper annular preventer does move slightly when the other valve actuators moves but as soon as the VBR closes, the bop pressure drops to only static head and the preventer closes fully.

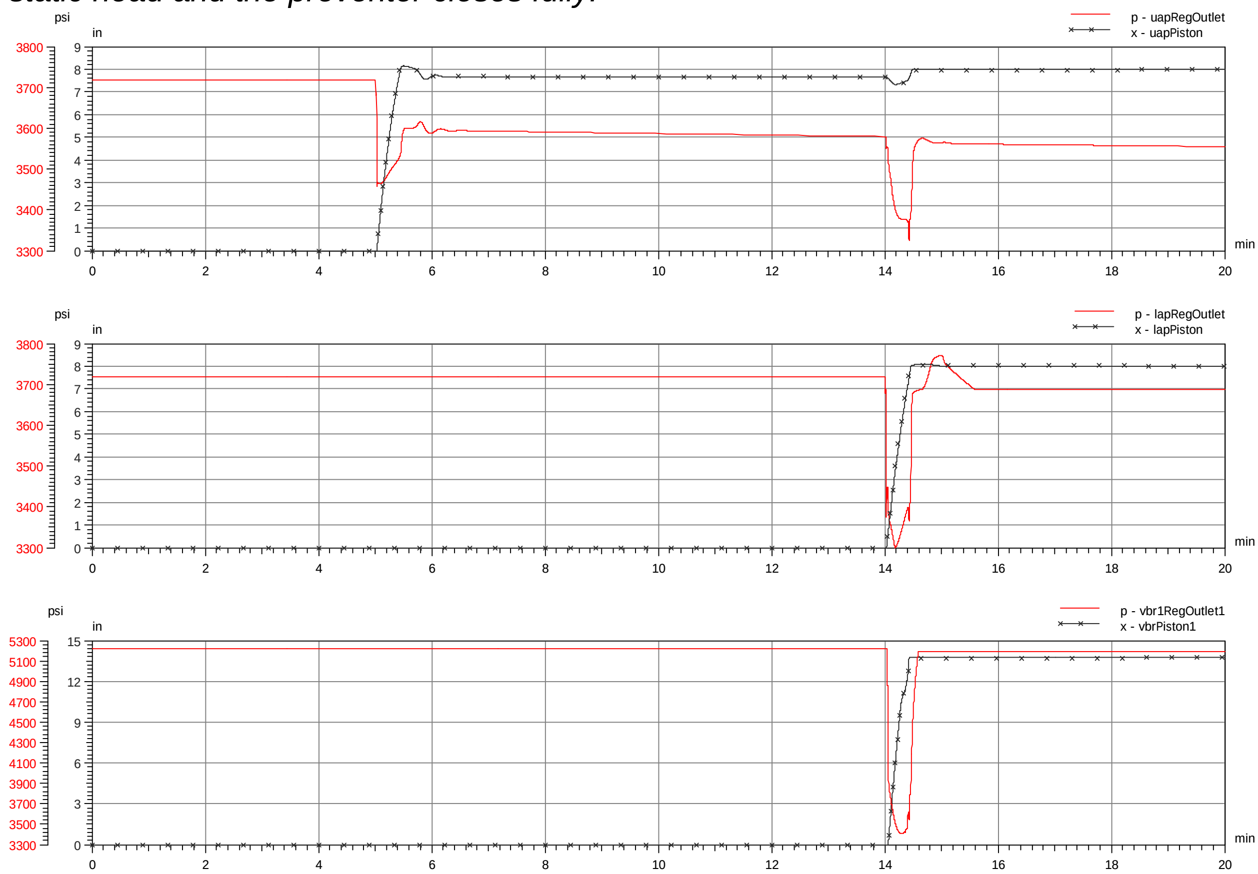


Figure 93) Pressure trends and actuator positions for Case 4-2b

Legend:	Description	Unit
p – uapRegOutlet	Pressure down stream of the UAP pressure regulator	psi
x – uapPiston	UAP actuator position	in
p – lapRegOutlet	Pressure down stream of the LAP pressure regulator	psi
x – lapPiston	LAP actuator position	in
p – vbr1RegOutlet	Pressure down stream of the VBR pressure regulator	psi
x – vbrPiston1	VBR actuator position	in

The pressure trend from the simplified well model can be seen in Figure 94) It gives a pressure build up which is close to the pressure behaviour in the real well. It also reflects the delay between BOP pressure and the logged stand pipe pressure on surface.

From this pressure log, it is not likely that closing one annular preventer with 1500 psi combined with a high BOP pressure starts to open the preventer again as seen in Figure 1) between 21:36 and 21:42. However it also shows that when the VBR closes, the stand pipe pressure increases fast as in the end of the pressure plot in Figure 1).

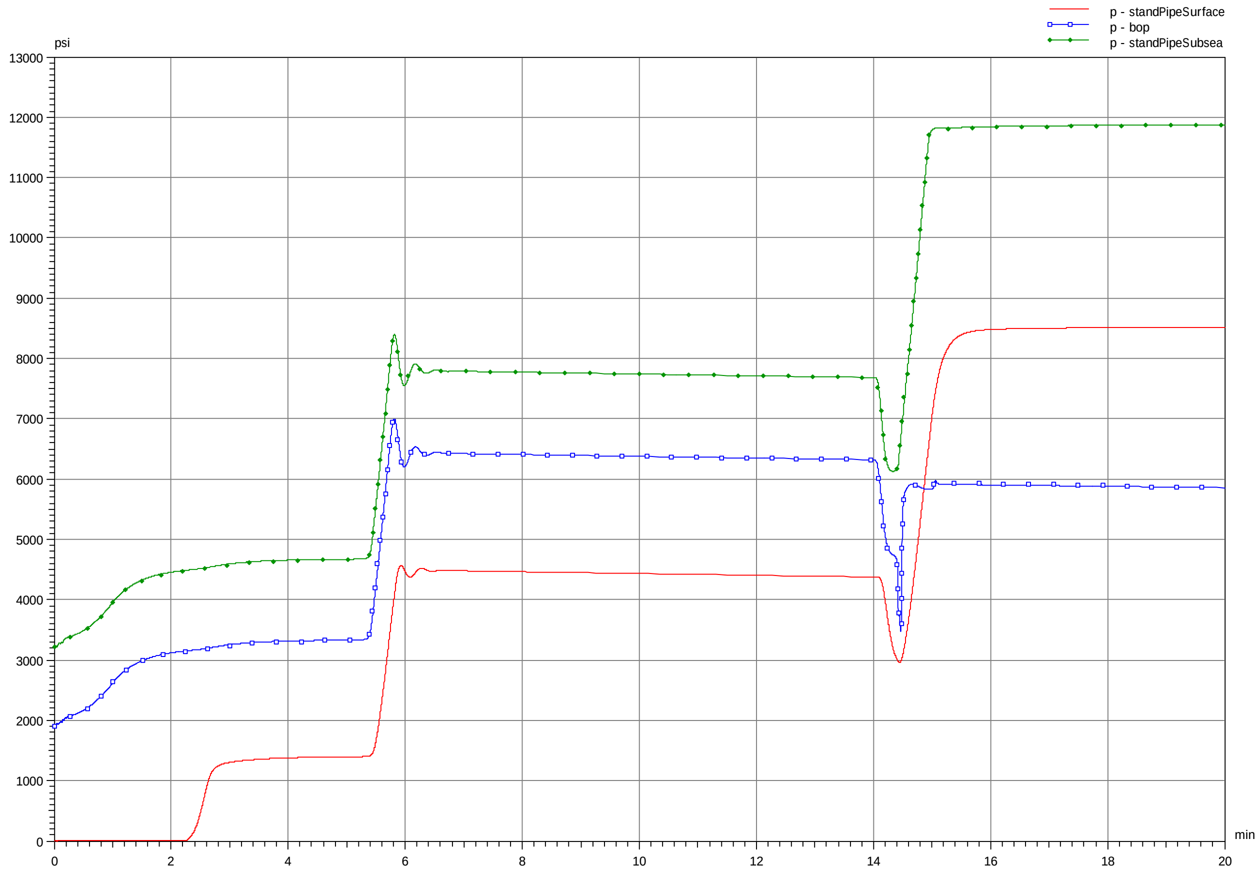


Figure 94) Pressure trends in simplified well model Case 4-2b

Legend:	Description	Unit
p – standpipeSurface	Surface Stand Pipe pressure	psi
p – bop	Pressure in BOP	psi
p – standPipeDH	Down Hole Stand Pipe pressure	psi

Figure 95) shows the LMRP accumulator pressure and volume. Since the leak rate is higher than the pump capacity, the leakage in the end will empty the supply accumulator system. At this point, the preventers will start to open.

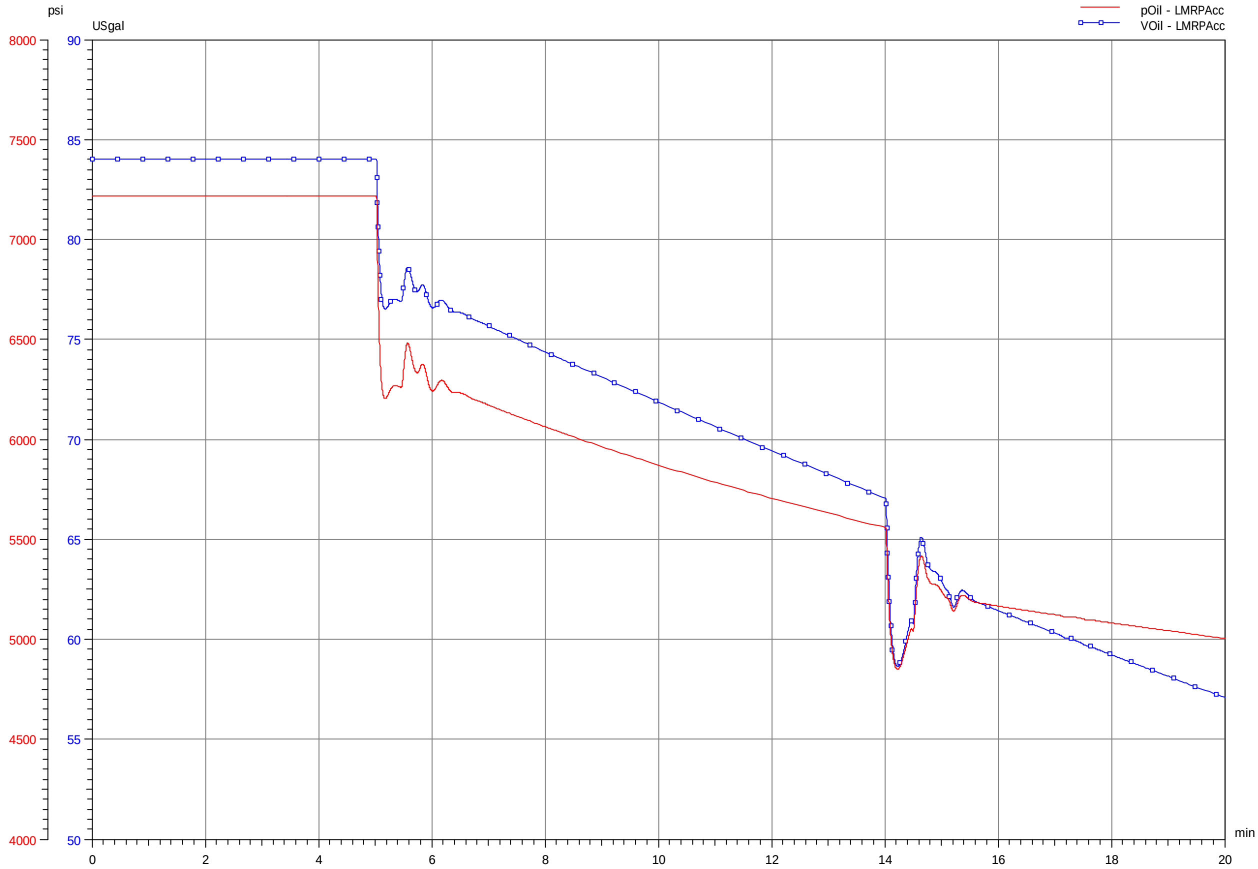


Figure 95) LMRP accumulator pressure and oil volume – Case 4-2b

Legend:	Description	Unit
pOil - LMRPAcc	Pressure in LMRP accumulators	psi
VOil - LMRPAcc	Total oil volume in LMRP accumulators	USgal

5.5 Scenario 5 – Operating the "EDS" with calculated DP shear force

The EDS system is designed to close the BSR and seal the well bore when the LMRP is disconnected from the BOP stack. The system automatically initiates a closure of the Blind Shear Ram driven from a 640 USgal accumulator volume.

The shear force required to cut the pipe is calculated using the "Cameron Shear Calculator". The output from the calculations is shown below.

Date: July 27, 2010

SHEARING PRESSURE CALCULATION FOR CAMERON 18-3/4" - 15,000 PSI WP "TL" RAM PREVENTER

Reference Document: Cameron EB 702 D, Rev. B9, dated January 21, 2008, titled "SHEARING CAPABILITIES OF CAMERON SHEAR RAMS", calculation for pressure required to shear pipe with OD and ID of drill pipe, and presence of wellbore pressure in calculation:

$$P_{SHEAR} = \frac{(((C_3 \cdot \sigma_{yield}) \cdot (pipe_{OD}^2 \cdot pipe_{ID}^2) \cdot 2.92) + P_W \cdot C_2)}{C_1}$$

Where:

P_{SHEAR} = calculated required operator pressure to shear (psi)

C_1 = BOP / Operator constant obtained from Table 2 of Cameron EB-702D. This corresponds to the piston rod closing area (in^2).

C_2 = BOP / Operator constant obtained from Table 2 of Cameron EB-702D. This corresponds to the piston rod opening area (in^2).

C_3 = the shear ram type / pipe grade constant from Table 3 of Cameron EB-702D. This is an empirical constant obtained from laboratory testing with various pipe grades and ram types.

P_W = Wellbore pressure at time of shear (psi)

σ_{yield} = yield strength of the tubular material

$pipe_{OD}$ = pipe / tube outside diameter (inches)

$pipe_{ID}$ = pipe / tube inside diameter (inches)

Wellbore Pressure = **0 psi**
Drill Pipe OD = **5,5 inches**
Tube Material, Grade S-135 = **135000 psi**
Minimum Nominal Tube Wall Thickness = **0,361 inches**
Min. Yield as allowed by API

C_1	C_2	C_3	OD	ID	σ_{yield}	P_W
238	36,00	0,23	5,500	4,78	135 000	-718

P_{SHEAR} = 2 718 psi

Note that this case is simulated with only 1500 psi BOP bore pressure which is 718 psi below the external seawater pressure since the EDS system was initiated after the incident and that the marine riser at this time was filled with hydrocarbons instead of water.

The BSR pipe shear sequence is modelled in SimulationX as shown in Figure 96). The BSRs are provided with one flat knife and one V-knife. Therefore the two actuators will stroke differently but it is assumed that both knives have the same shear properties. The drill pipe has an OD of 5.5 inches and an ID of 4.78 inches.

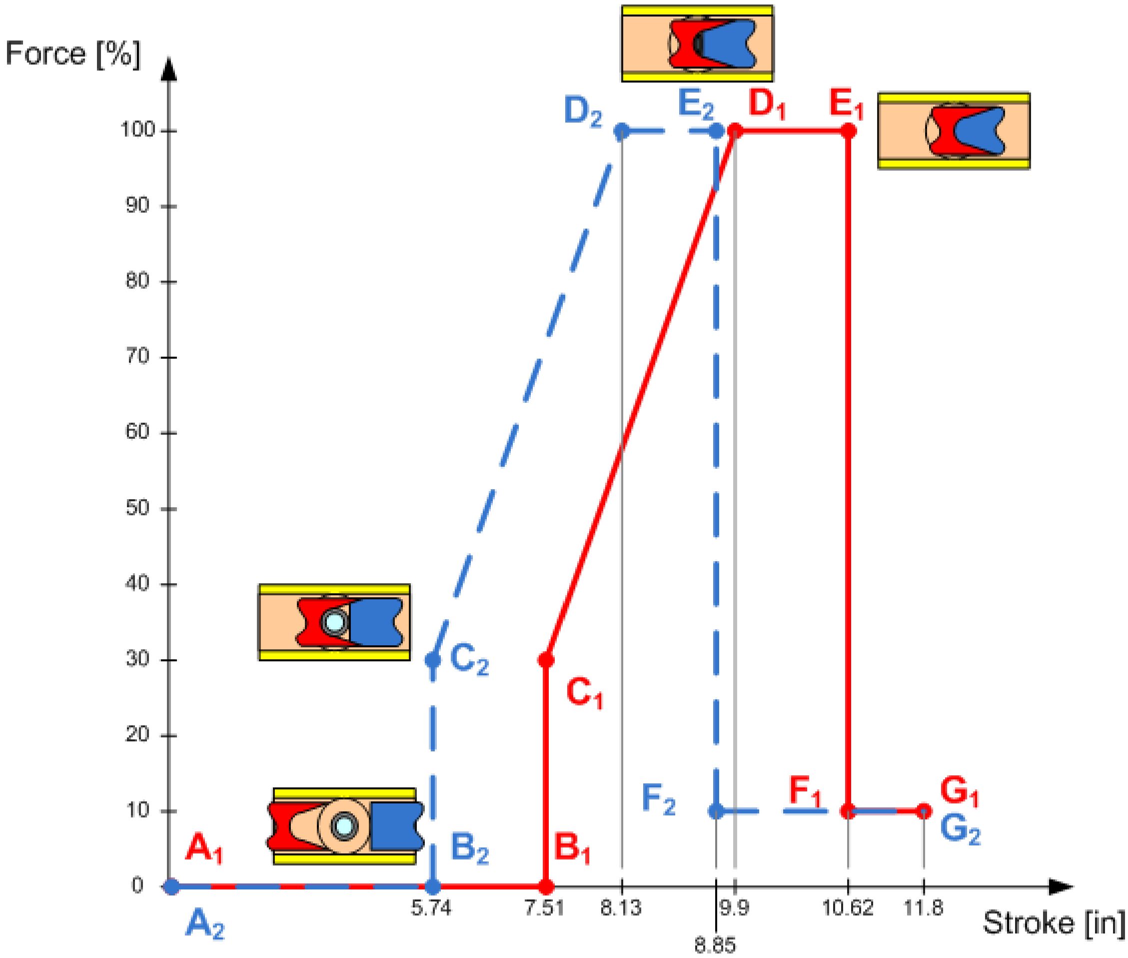


Figure 96) BSR pipe shear sequence

Point	Description	Stroke length Actuator 1	Stroke length Actuator 2	Actuator Shear Pressure
A	BSR Actuator in fully Open position	0 in	0 in	0 psi
B	BSR knives stroke out and touches the pipe wall	7.51 in	5.74 in	0 psi
C	Pressure builds up in the BSR actuator and the BSR knives start to squeeze the pipe from OD 5.5 in	7.51 in	5.74 in	848.1 psi
D	The drill pipe is fully squeezed from OD 5.5 in to 2 x WT (0.72 in). Knifes starts to cut the pipe walls.	9.9 in	8.13 in	2827 psi
E	BSR knives have cut through the pipe walls and required shear force drops.	10.62 in	8.85 in	2827 psi
F	BSR knives overlaps and BSR actuator strokes to end stop.	10.62 in	8.85 in	282.7 psi
G	BSR actuator in end stop fully closed	11.8 in	11.8 in	282.7 psi

The shear sequence is estimated from experiences since there are no geometrical drawings available. The estimated stroke lengths before the knives reaches the pipe wall can be different on the real BSR but this will not influence on the calculated shear pressure.

Figure 97) shows the shear pressure for the BSR actuators. As can be seen, the two curves corresponds with Figure 96) and belonging table.

There is a negative pressure spike in actuator 2 at a stroke length of close to 9 inches. This is the point where actuator 1 reaches its end stop.

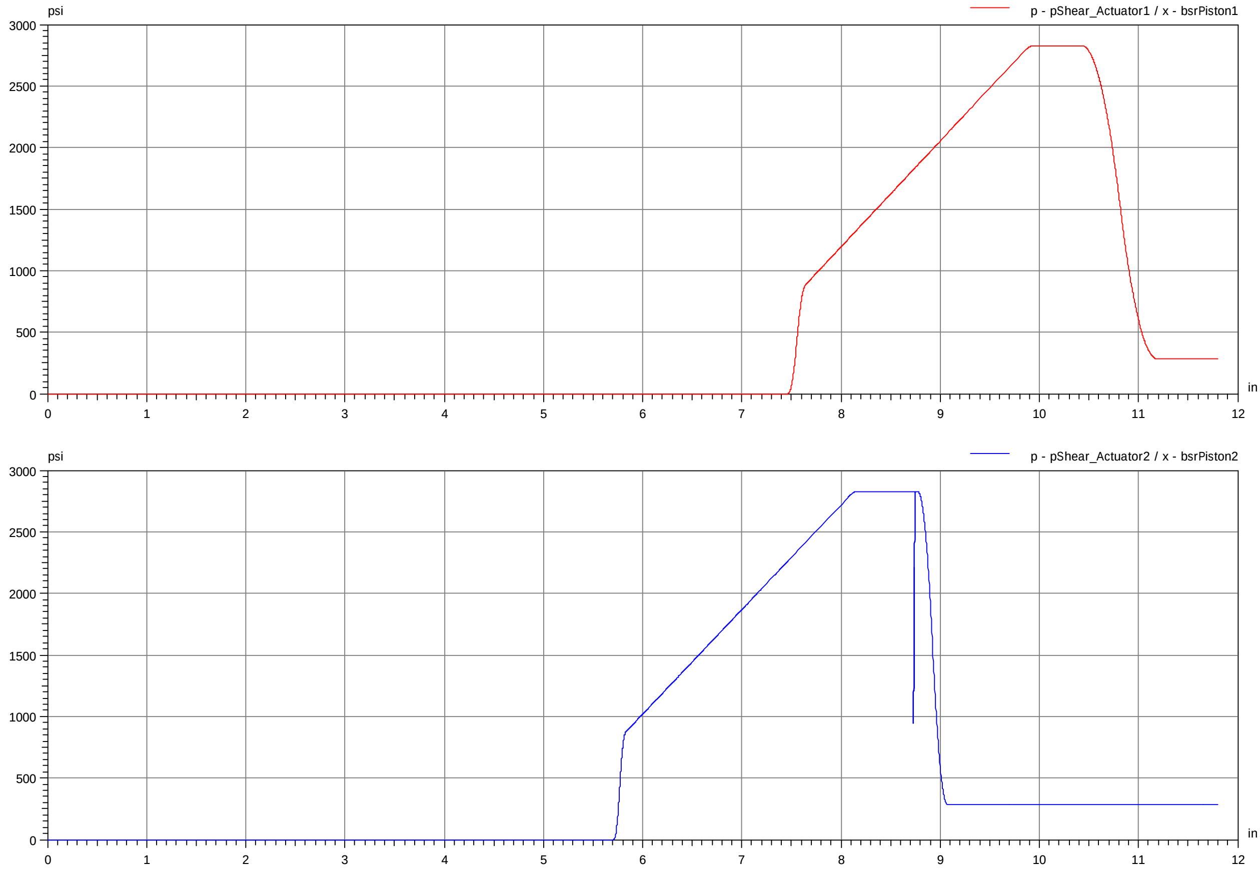


Figure 97) BSR shear pressure curves – Case 5

Legend:	Description	Unit
p – pShear_Actuator1	Shear pressure for BSR Actuator 1 – with V knife	psi
x – bsrPiston1	Blind shear ram piston position	in
p – pShear_Actuator2	Shear pressure for BSR Actuator 2 – with flat knife	psi
x – bsrPiston2	Blind shear ram piston position	in

5.5.1 Case 5-1: Operation of the "Auto Shear" function

5.5.1.1 Case 5-1a: Normal operation

Figure 98) shows the BSR actuator 1 and ST Lock strokes together with the BSR Open and Close pressures when closing and cutting drill pipe at 5000 meter water depth and 1500 psi in the BOP.

The actuator starts to close at 1.5 seconds. The V-knife reaches the pipe at 6.3 seconds and the pressure builds up until it is enough to start squeezing the pipe.

At 10.3 seconds, the V-knife start to shear the pipe and at 11.3 seconds it is through the pipe and the ST Lock starts to close.

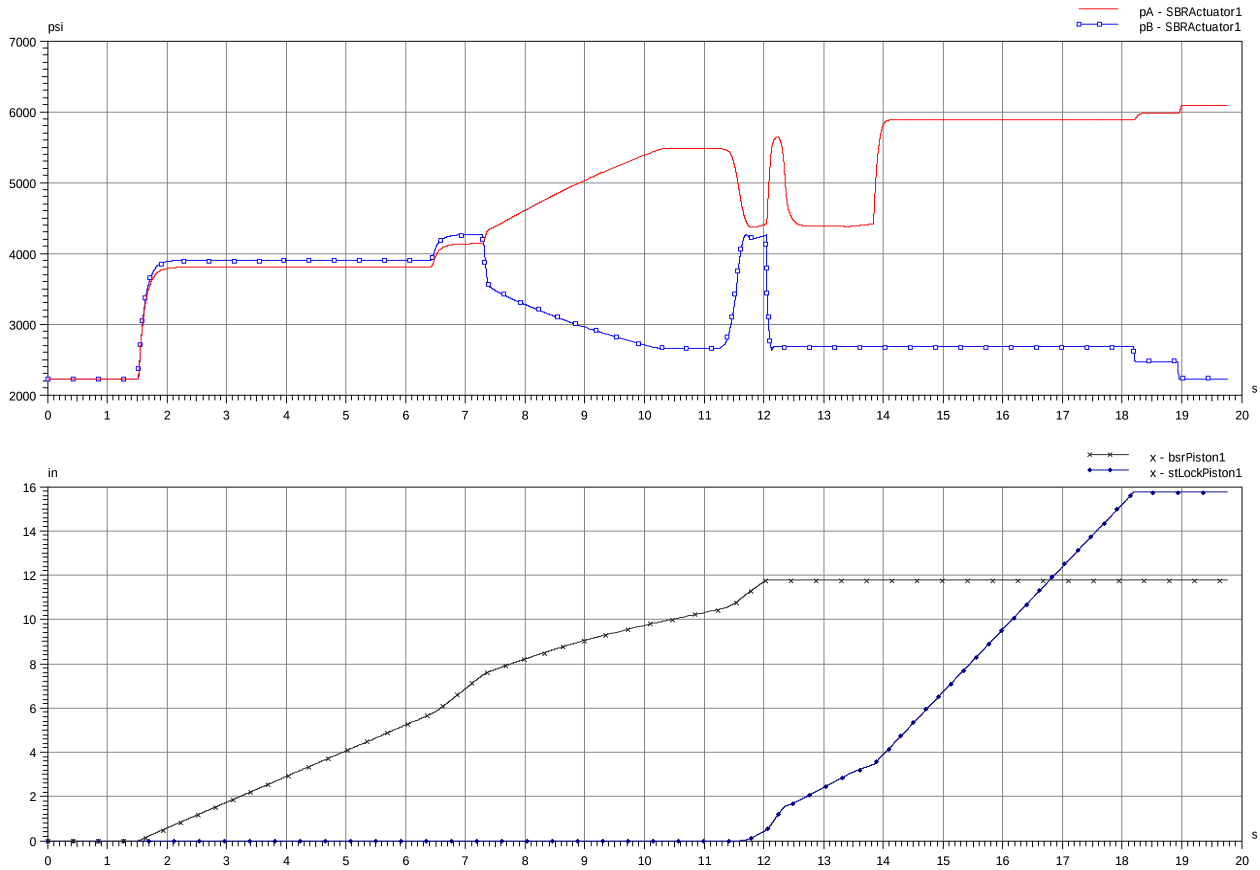


Figure 98) Actuator 1 Open/close pressure and actuator position – Case 5-1a

Legend:	Description	Unit
pA – bsrActuator1	Pressure in BSR actuator 1 Close cavity	psi
pB – bsrActuator1	Pressure in BSR actuator 1 Open cavity	psi
x – bsrPiston1	BSR actuator 1piston position	in
x – stLockPiston1	ST Lock position	in

Figure 99) shows the BSR actuator 2 and ST Lock strokes together with the SBR Open and Close pressures when closing and cutting drill pipe at 5000 meter water depth and 1500 psi in the BOP.

The actuator starts to close at 1.5 seconds. The flat knife reaches the pipe at 6.4 seconds and the stroke stops until 7.3 seconds when Actuator 1 has reached the pipe. The pressure builds up in parallel with actuator 1 and both actuators starts to cut the pipe at 10.3 seconds.

Actuator 1 is through the pipe walls at 11.3 seconds. At this point, actuator 2 stops until actuator 1 reaches its end stop and pressure can build up again. At 12.1 second is also Actuator 2 through the pipe walls and moves fast to its end stop.

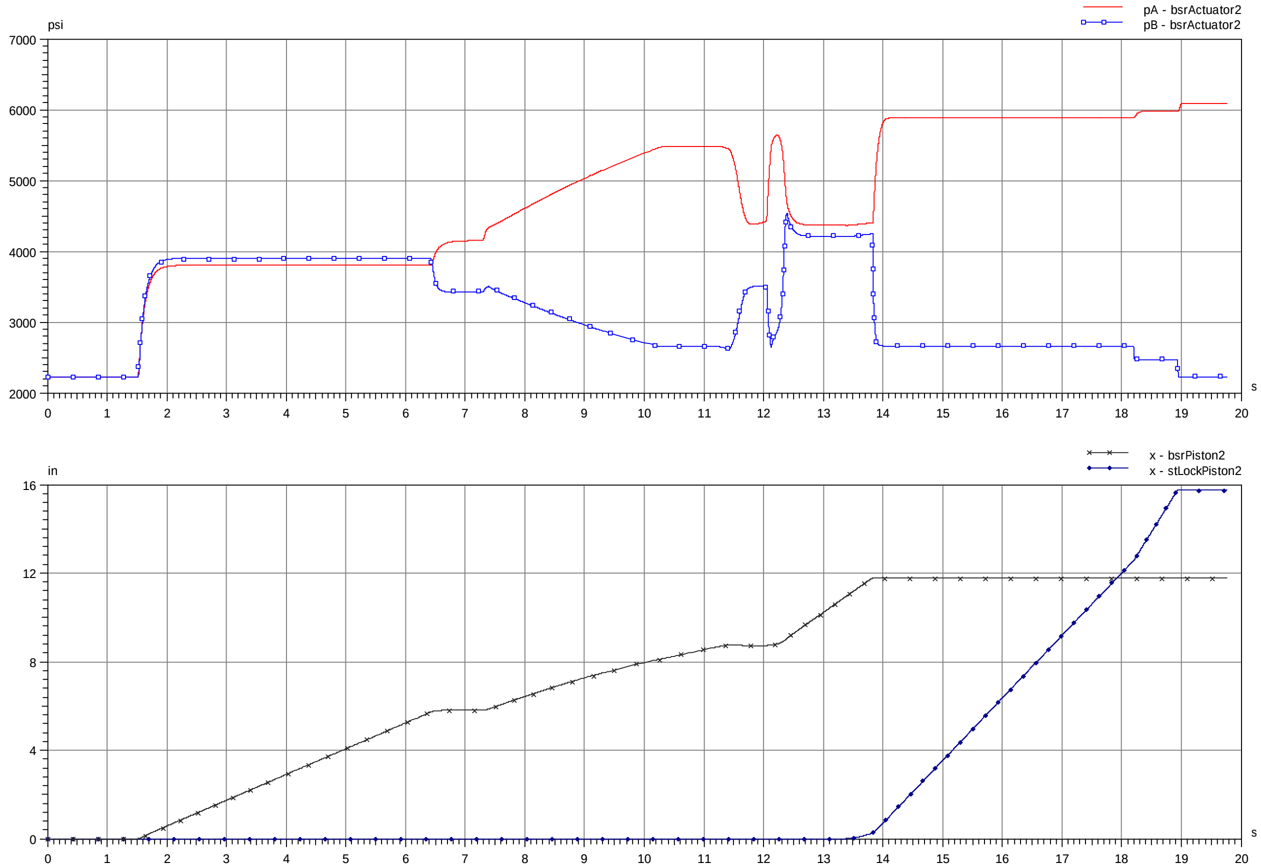


Figure 99) Actuator 2 Open/close pressure and actuator position – Case 5-1a

Legend:	Description	Unit
pA – bsrActuator2	Pressure in BSR actuator 2 Close cavity	psi
pB – bsrActuator2	Pressure in BSR actuator 2 Open cavity	psi
x – bsrPiston2	BSR actuator piston position	in
x – stLockPiston2	ST Lock position	in

The “Auto Shear Accumulators” has a total shell-voume of 640 USgal. The accumulators are pre-charged with gas (N2) to 5500 psi at surface and charged to 5000 psi + static head (2218 psi) with fluid subsea.

Resulting available volume is 126.8 USgal. After the stroke, the volume is dropped to 95.9 USgal. Minimum pressure after the stroke is found to be 6042 psi.

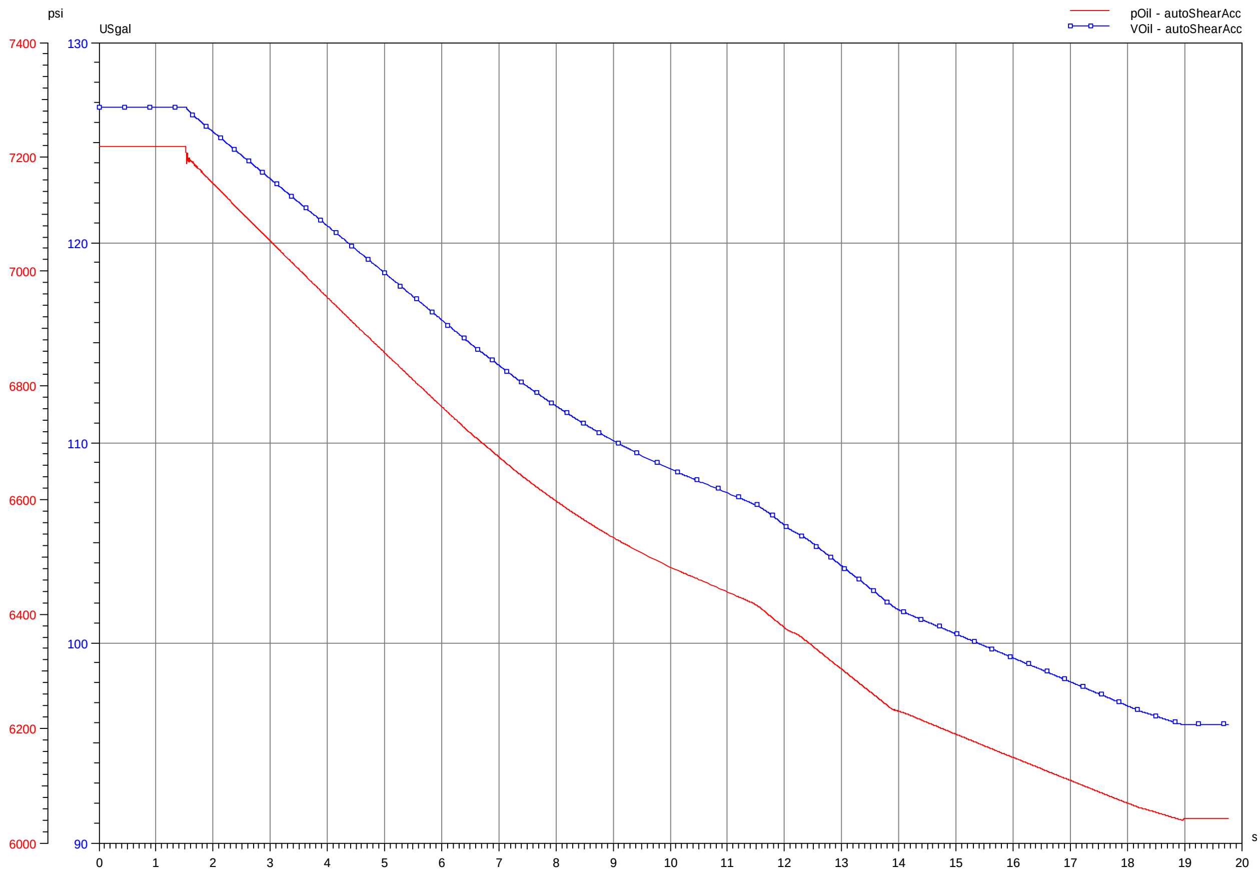


Figure 100) “Auto Shear” accumulator pressure and oil volume – Case 5-1a

Legend:	Description	Unit
pOil - autoShearAcc	Pressure in “Auto Shear Accumulators”	psi
VOil - autoShearAcc	Oil volume in “Auto Shear Accumulators”	USgal

5.5.1.2 Case 5-1b: Operation with reduced accumulator volume

This case is simulated to find how many of the 8 “auto shear” accumulators that can be out of function (out of pre-charged gas) before the system cant shear the drill pipe.

This case is set up with 3 of 8 accumulators active. Resulting accumulator volume is 240 USgal.

Figure 101) shows the BSR actuator 1 and ST Lock strokes together with the BSR Open and Close pressures when closing and cutting drill pipe at 5000 meter water depth and 1500 psi in the BOP.

The actuator starts to close at 1.5 seconds. The V-knife reaches the pipe at 7.3 seconds and the pressure builds up until it is enough to start squeezing the pipe.

At 10.8 seconds, the V-knife start to shear the pipe and at 12.4 seconds it is through the pipe and the ST Lock starts to close.

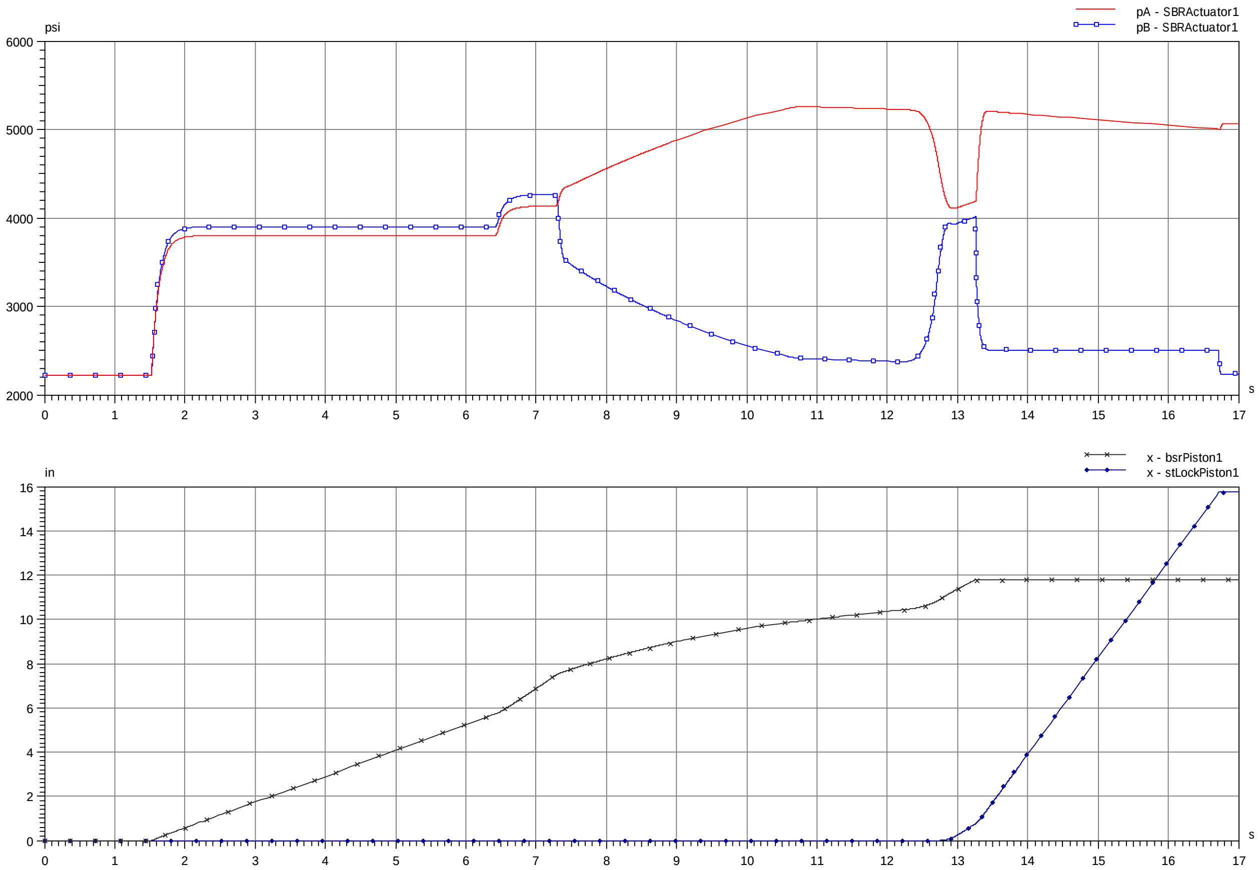


Figure 101) Actuator 1 Open/close pressure and actuator position – Case 5-1b

Legend:	Description	Unit
pA – bsrActuator1	Pressure in BSR actuator 1 Close cavity	psi
pB – bsrActuator1	Pressure in BSR actuator 1 Open cavity	psi
x – bsrPiston1	BSR actuator 1piston position	in
x – stLockPiston1	ST Lock position	in

Figure 102) shows the BSR actuator 2 and ST Lock strokes together with the SBR Open and Close pressures when closing and cutting drill pipe at 5000 meter water depth and 1500 psi in the BOP.

The actuator starts to close at 1.5 seconds. The flat knife reaches the pipe at 6.4 seconds and the stroke stops until 7.3 seconds when Actuator 1 has reached the pipe. The pressure builds up in parallel with actuator 1 and both actuators starts to cut the pipe at 10.3 seconds.

Actuator 1 is through the pipe walls at 11.3 seconds. At this point, actuator 2 stops until actuator 1 reaches its end stop and pressure can build up again. As can be seen, the accumulators do not have enough energy left to continue the cutting sequence when actuator 1 has reached end stop.

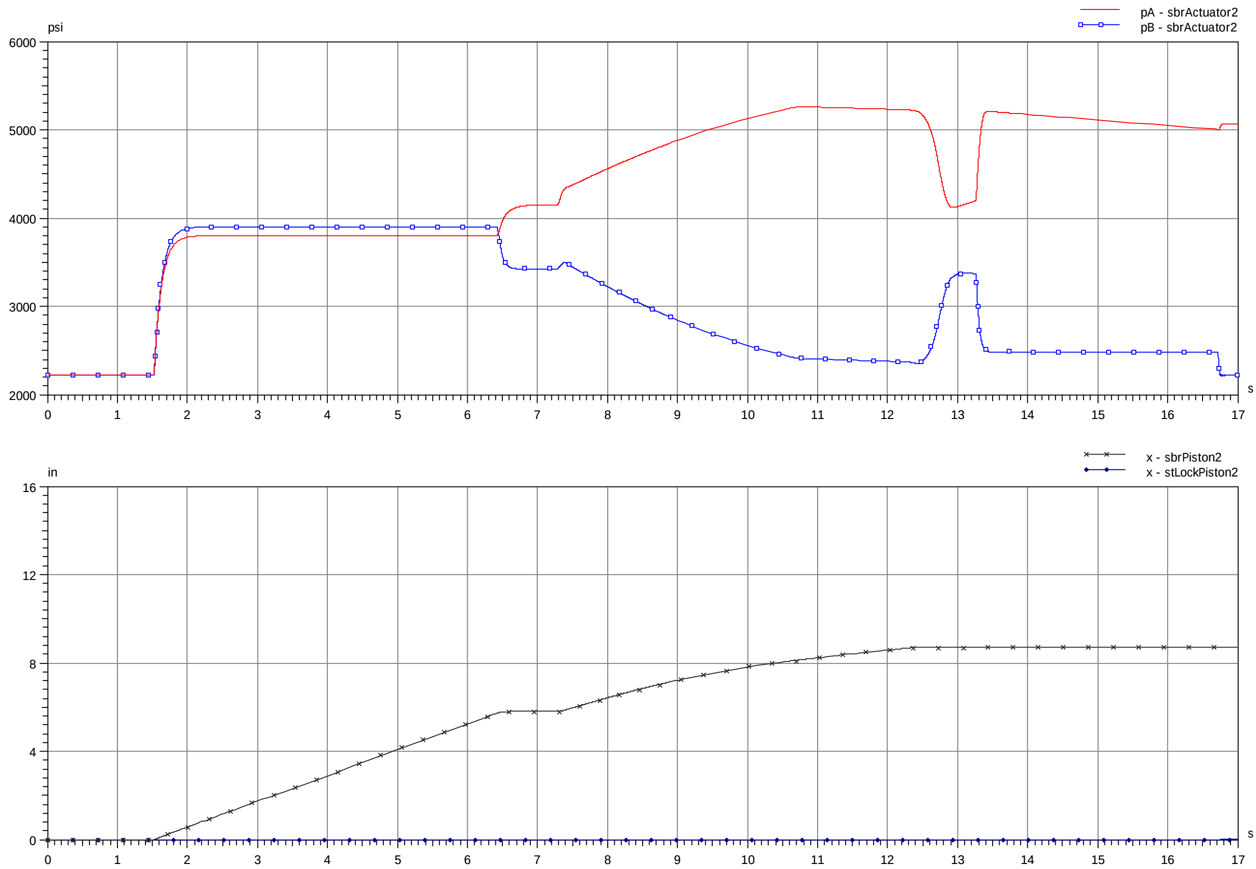


Figure 102) Actuator 2 Open/close pressure and actuator position – Case 5-1b

Legend:	Description	Unit
pA – bsrActuator2	Pressure in BSR actuator 2 Close cavity	psi
pB – bsrActuator2	Pressure in BSR actuator 2 Open cavity	psi
x – bsrPiston2	BSR actuator piston position	in
x – stLockPiston2	ST Lock position	in

The “Auto Shear Accumulators” has a total shell-volume of 640 USgal. In this case, 5 of 8 accumulators are out of operation and the resulting accumulator volume is only 240 US gal. The accumulators are pre-charged with gas (N2) to 5500 psi at surface and charged to 5000 psi + static head (2218 psi) with fluid subsea.

Accumulator rest volume is 23.7 USgal with a pressure of 5067 psi (2849 + static head) when the shear sequence stops.

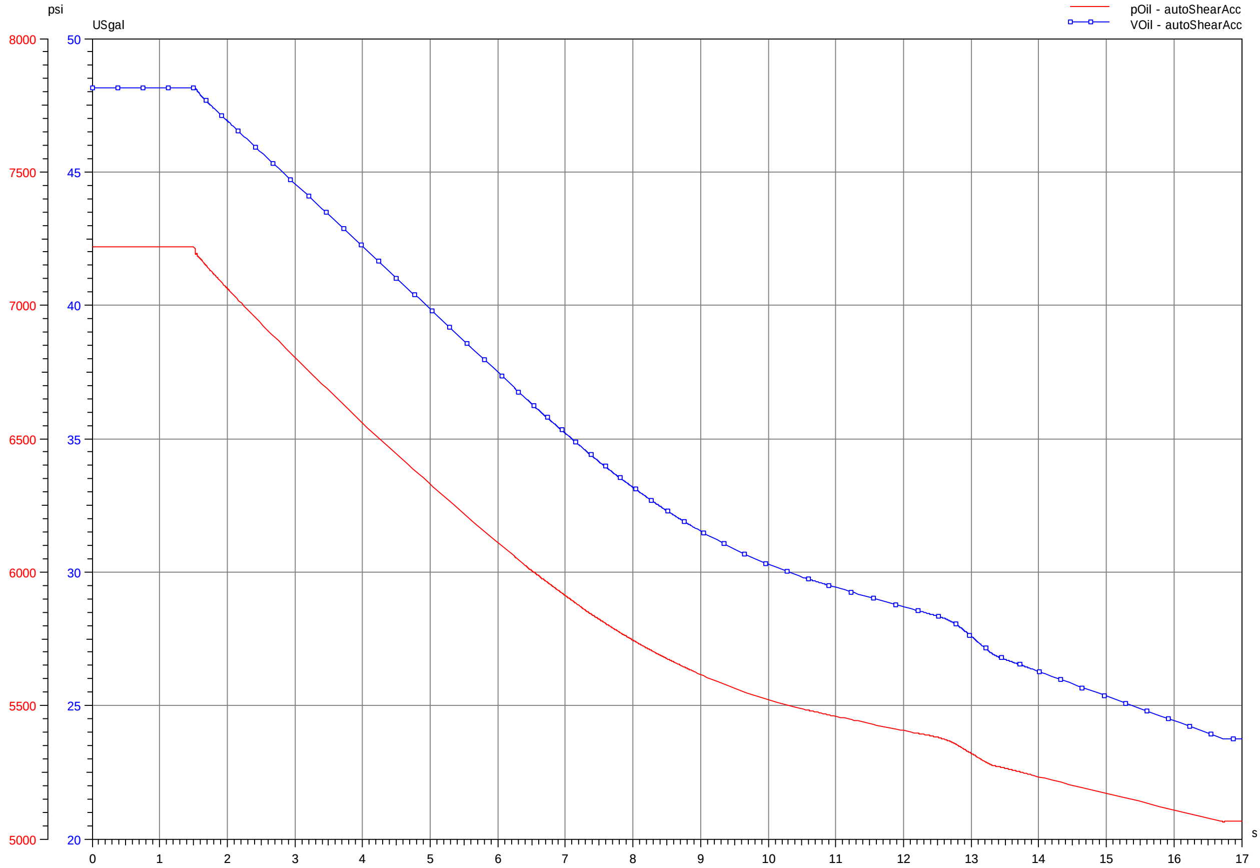


Figure 103) “Auto Shear” accumulator pressure and oil volume – Case 5-1b

Legend:	Description	Unit
pOil - autoShearAcc	Pressure in “Auto Shear Accumulators”	psi
VOil - autoShearAcc	Oil volume in “Auto Shear Accumulators”	USgal

5.5.1.3 Case 5-1c: Operation with reduced system pressure

This case is simulated to find at which initial system/accumulator pressure the “auto shear” function fail to shear the drill pipe

This case is set up with 5638 psi initial accumulator pressure (3420 psi + static head) in the “auto shear” accumulators. There is no additional supply from surface during the sequence.

Figure 104) shows the BSR actuator 1 and ST Lock strokes together with the BSR Open and Close pressures when closing and cutting drill pipe at 5000 meter water depth and 1500 psi in the BOP.

The actuator starts to close at 1.5 seconds. The V-knife reaches the pipe at 7.6 seconds and the pressure builds up until it is enough to start squeezing the pipe.

At 12 seconds, the V-knife start to shear the pipe and at 15.5 seconds it is through the pipe and the ST Lock starts to close.

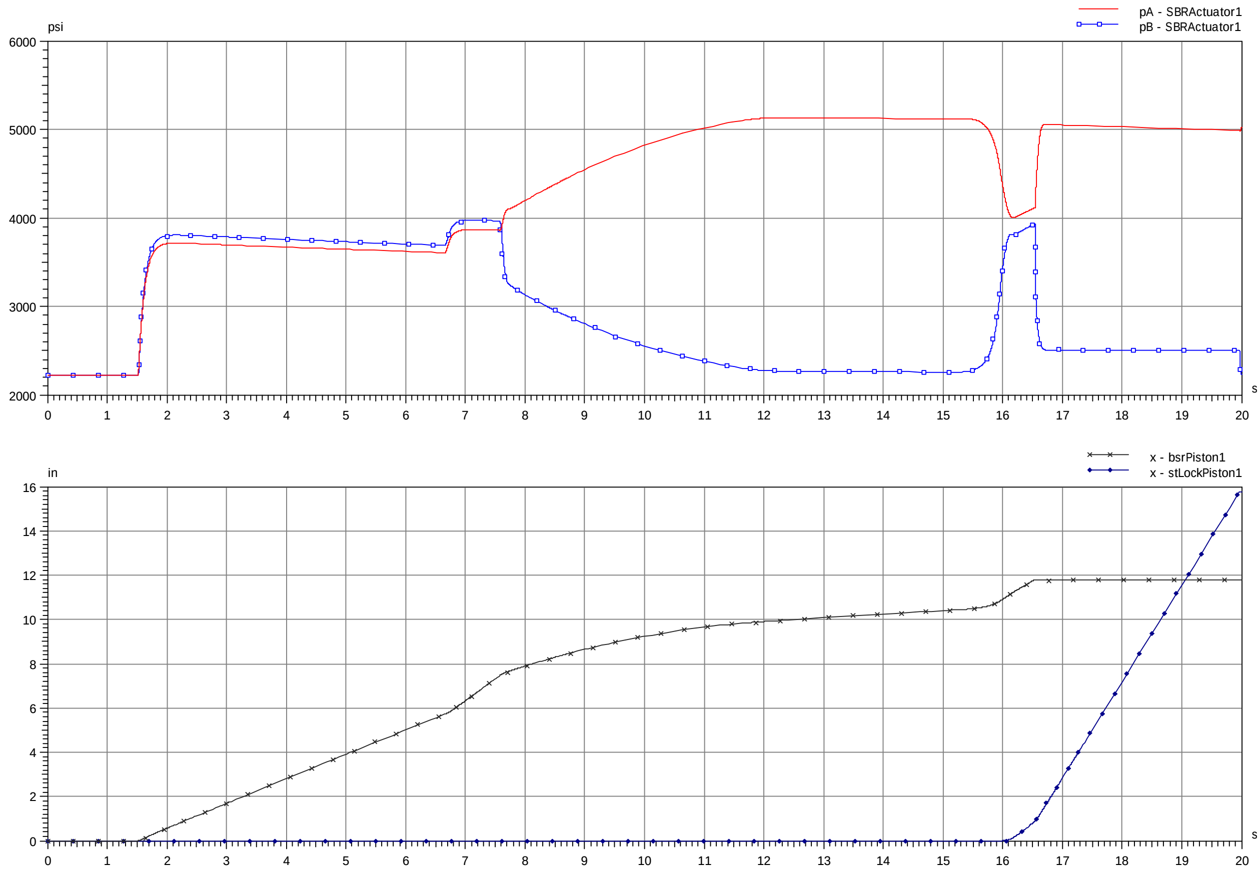


Figure 104) Actuator 1 Open/close pressure and actuator position – Case 5-1c

Legend:	Description	Unit
pA – bsrActuator1	Pressure in BSR actuator 1 Close cavity	psi
pB – bsrActuator1	Pressure in BSR actuator 1 Open cavity	psi
x – bsrPiston1	BSR actuator 1piston position	in
x – stLockPiston1	ST Lock position	in

Figure 105) shows the BSR actuator 2 and ST Lock strokes together with the SBR Open and Close pressures when closing and cutting drill pipe at 5000 meter water depth and 1500 psi in the BOP.

The actuator starts to close at 1.5 seconds. The flat knife reaches the pipe at 6.7 seconds and the stroke stops until 7.6 seconds when Actuator 1 has reached the pipe. The pressure builds up in parallel with actuator 1 and both actuators starts to cut the pipe at 12 seconds.

Actuator 1 is through the pipe walls at 15.5 seconds. At this point, actuator 2 stops until actuator 1 reaches its end stop and pressure can build up again. As can be seen, the accumulators do not have enough energy left to continue the cutting sequence when actuator 1 has reached end stop.

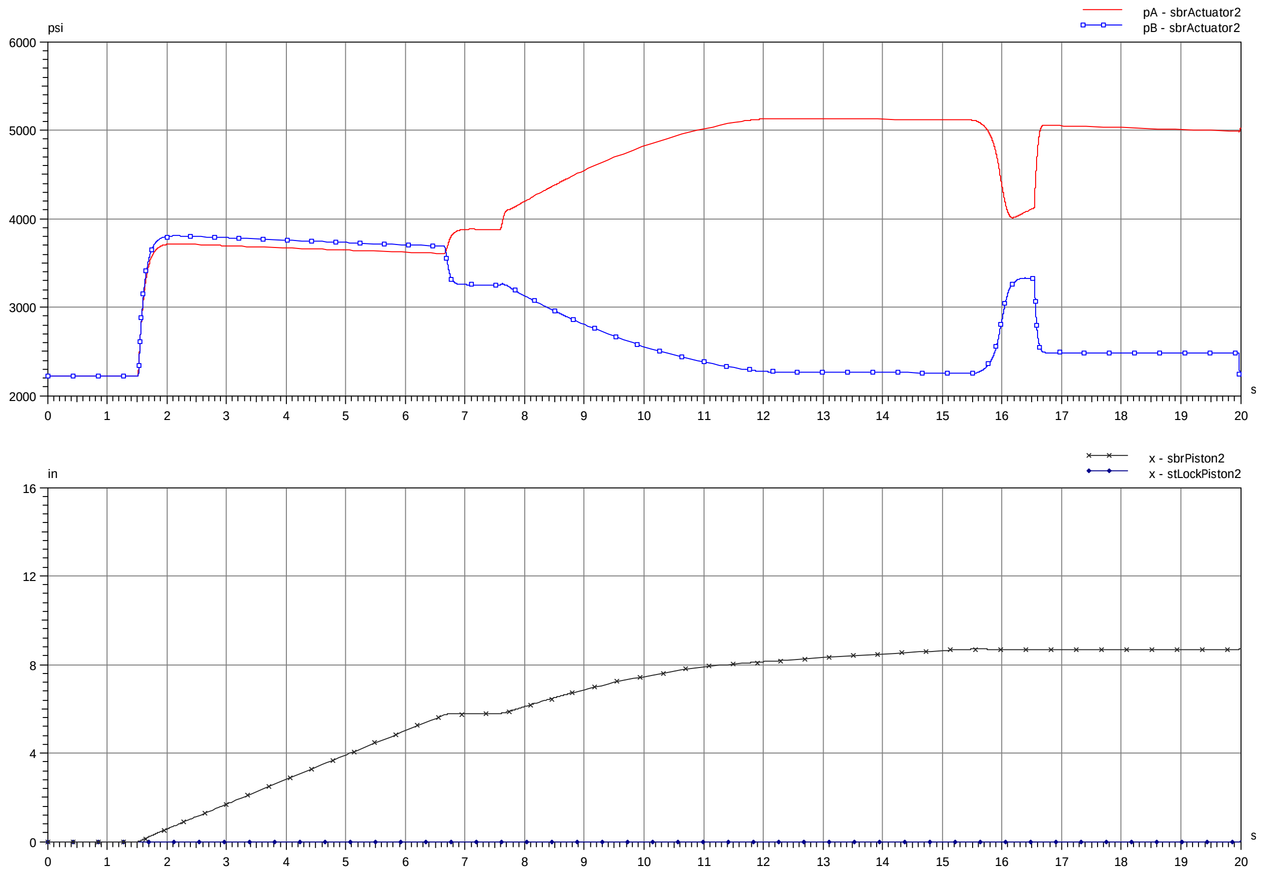


Figure 105) Actuator 2 Open/close pressure and actuator position – Case 5-1c

Legend:	Description	Unit
pA – bsrActuator2	Pressure in BSR actuator 2 Close cavity	psi
pB – bsrActuator2	Pressure in BSR actuator 2 Open cavity	psi
x – bsrPiston2	BSR actuator piston position	in
x – stLockPiston2	ST Lock position	in

The “Auto Shear Accumulators” has a total shell-volume of 640 USgal. In this case, the initial system/accumulator pressure is reduced from 5000 psi to 3420 psi. Initial available oil volume is 46.4 USgal.

Accumulator rest volume is 21.7 USgal with a pressure of 5050 psi (2832 + static head) when the shear sequence stops.

Figure 106) “Auto Shear” accumulator pressure and oil volume – Case 5-1c

Legend:	Description	Unit
pOil - autoShearAcc	Pressure in “Auto Shear Accumulators”	psi
VOil - autoShearAcc	Oil volume in “Auto Shear Accumulators”	USgal

5.5.2 Case 5-2: Operating the "Auto Shear" system with leakage in ST-Lock line

5.5.2.1 Leak Rate Cv 3 and 4200 psi BOP bore pressure

There is reported a leakage in the ST-lock line in an internal leak review dated June 7, 2010. The leakage is reported to be "significant" and an ROV was not able to build up pressure with a pump supplying 8 USgal/min.

Note:
Several simulation runs with required cutting pressure of 2827 psi, BOP bore pressure of 1500 psi and different leak rates in the ST-Lock shuttle valve connection has been performed. There is not possible to find a practical leak rate which will prevent the BSR to shear and close under these conditions.
Therefore, this case is performed with 4200 psi BOP pressure instead of 1500 as in previous case.

The model is set up with a leakage in the ST-Lock shuttle valve connection. The leakage is modelled as a sharp edge orifice with a Cv of 3. Figure 107) shows the flow through the leak orifice as function of the pressure difference across the orifice.

Maximum flow is found to be 81.4 USgal/min at pressure difference of 745.6 psi.

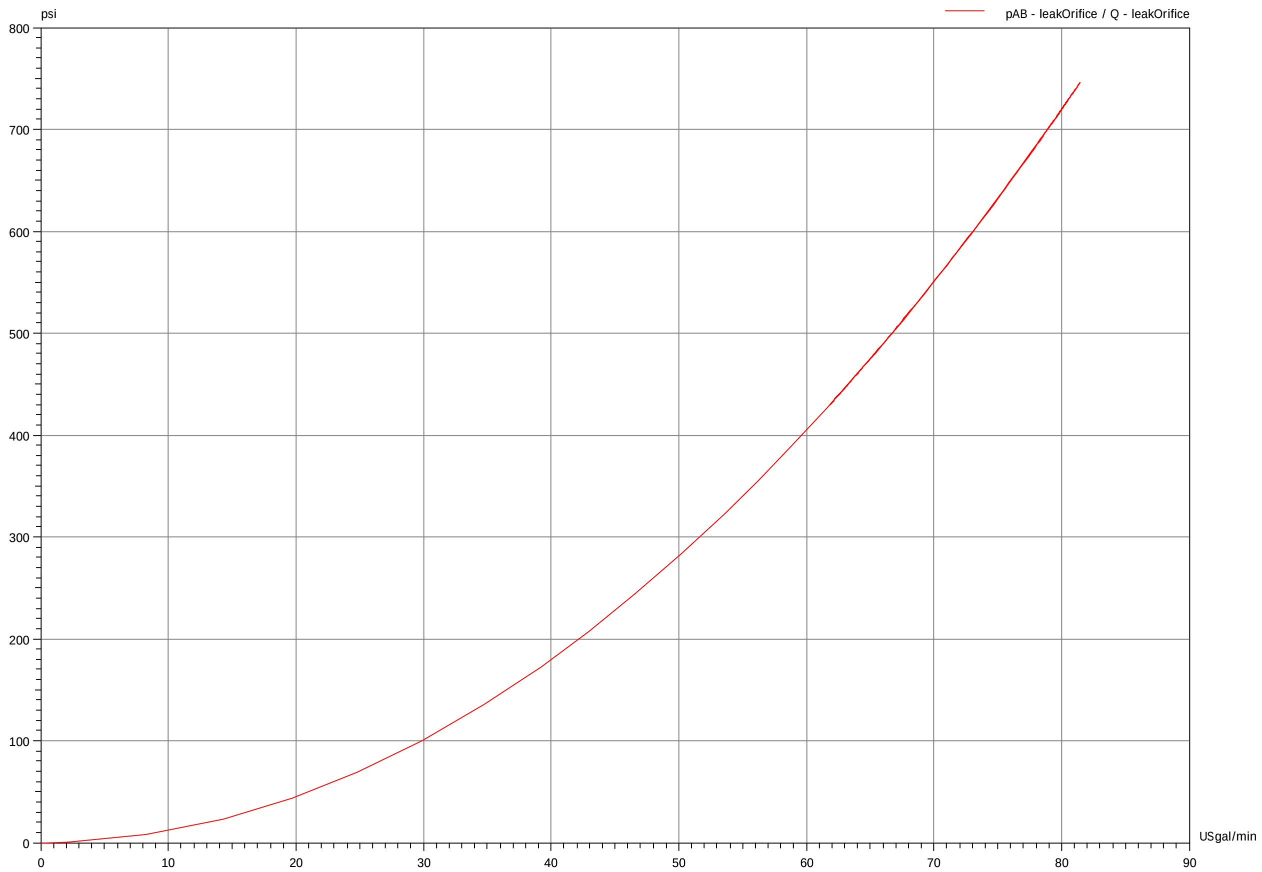


Figure 107) Leak Flow in the ST-Lock line – Case 5-2

Legend:	Description	Unit
pAB - leakOrifice	Pressure difference across the orifice	psi
Q – leakOrifice	Flow through the leak orifice.	USgal/min

Figure 108) shows the BSR actuator and ST Lock strokes together with the BSR Open and Close pressures for actuator 1 when closing and cutting drill pipe at 5000 meter water depth, 4200 psi in the BOP bore and a leakage in the ST-Lock line.

The actuator starts to close at 1.5 seconds. The V-knife reaches the pipe at 8.4 seconds and the pressure builds up until it is enough to start squeezing the pipe.

At 13 seconds, the V-knife start to shear the pipe and at 15.6 seconds it is through the pipe and the ST Lock starts to close.

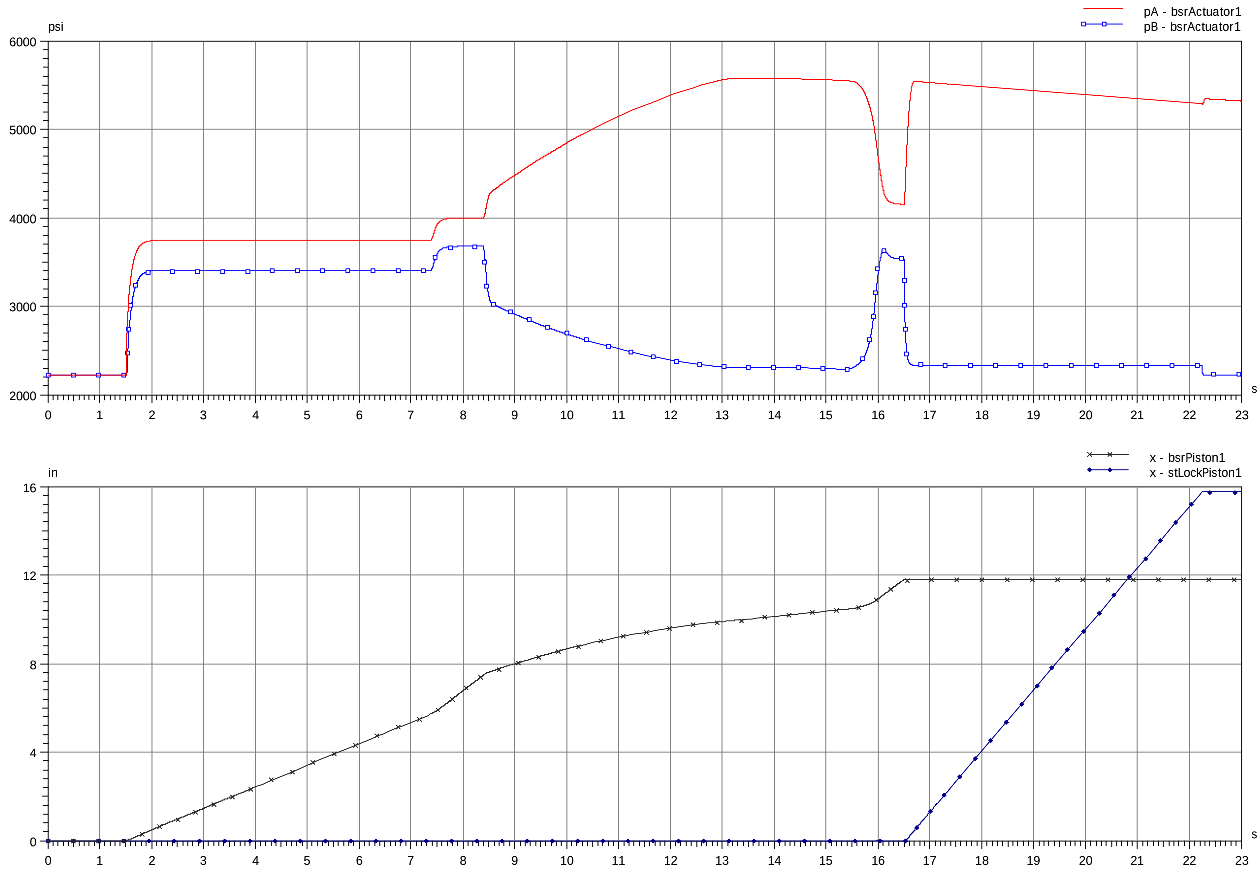


Figure 108) Actuator 1 Open/close pressure and actuator position – Case 5-2

Legend:	Description	Unit
pA – bsrActuator1	Pressure in BSR actuator 1 Close cavity	psi
pB – bsrActuator1	Pressure in BSR actuator 1 Open cavity	psi
x – bsrPiston1	BSR actuator 1 piston position	in
x – stLockPiston1	ST Lock position	in

Figure 109) shows the BSR actuator and ST Lock strokes together with the BSR Open and Close pressures for actuator 2 when closing and cutting drill pipe at 5000 meter water depth, 4200 psi in the BOP bore and a leakage in the ST-Lock line.

The actuator starts to close at 1.5 seconds. The flat knife reaches the pipe at 7.4 seconds and the stroke stops until 8.4 seconds when Actuator 1 has reached the pipe. The pressure builds up in parallel with Actuator 1 and both actuators starts to cut the pipe at 13 seconds.

Actuator 1 is through the pipe walls at 15.6 seconds. At this point, actuator 2 stops until actuator 1 reaches its end stop and pressure starts to build up again. The leakage in the ST-Lock line has in the mean time bled out fluid from the “Auto Shear” accumulators and there is not enough capacity left to build up the pressure to required shear pressure. Actuator 2 stops at a stroke length of 8.7 inches which is 0.15 inches from full shear of the pipe.

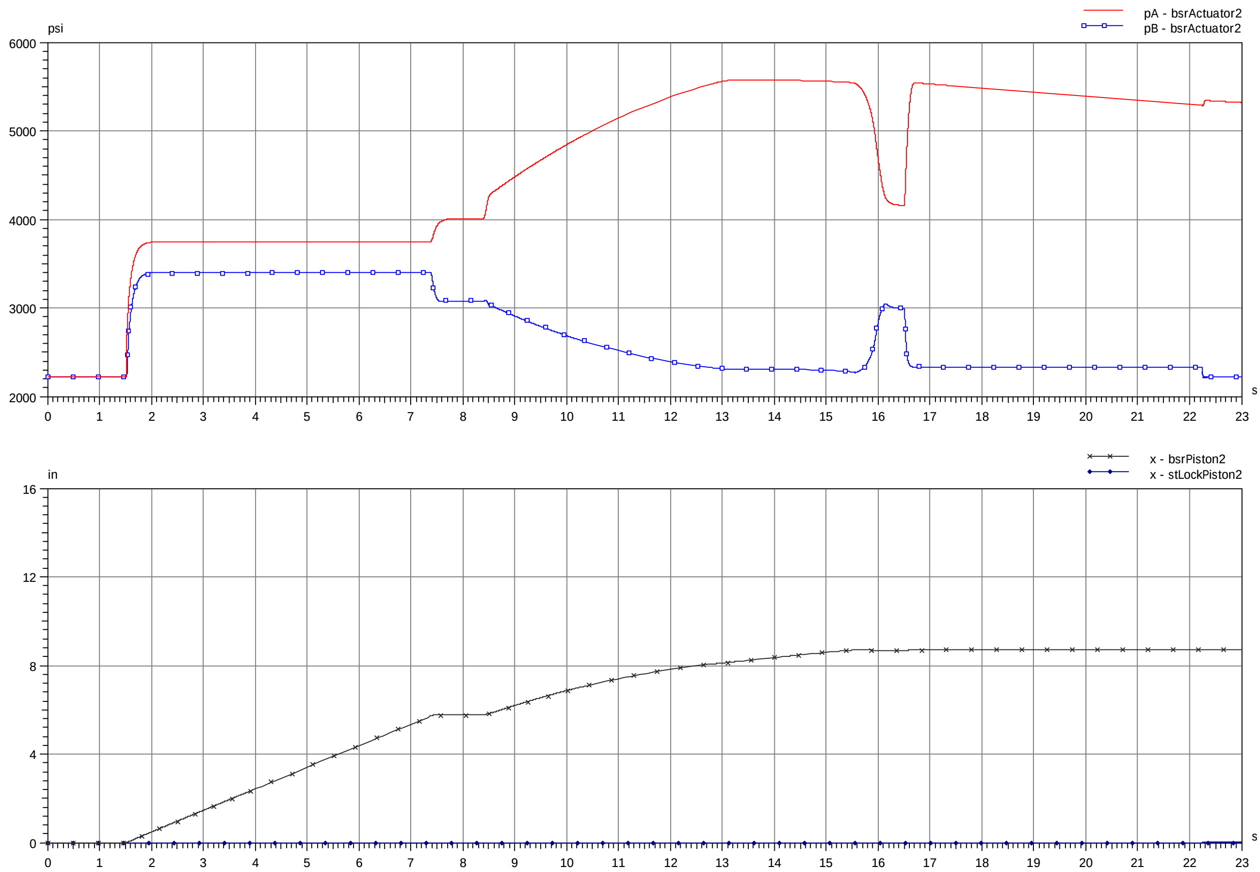


Figure 109) Actuator 2 Open/close pressure and actuator position – Case 5-2

Legend:	Description	Unit
pA – bsrActuator2	Pressure in BSR actuator 2 Close cavity	psi
pB – bsrActuator2	Pressure in BSR actuator 2 Open cavity	psi
x – bsrPiston2	BSR actuator 2 piston position	in
x – stLockPiston2	ST Lock position	in

As can be seen from the pressure and volume trend plot in Figure 110), the leakage causes a loss of hydraulic fluid and the “Auto Shear” system will not be able to cut the 5 ½” Drill pipe and close under these conditions.

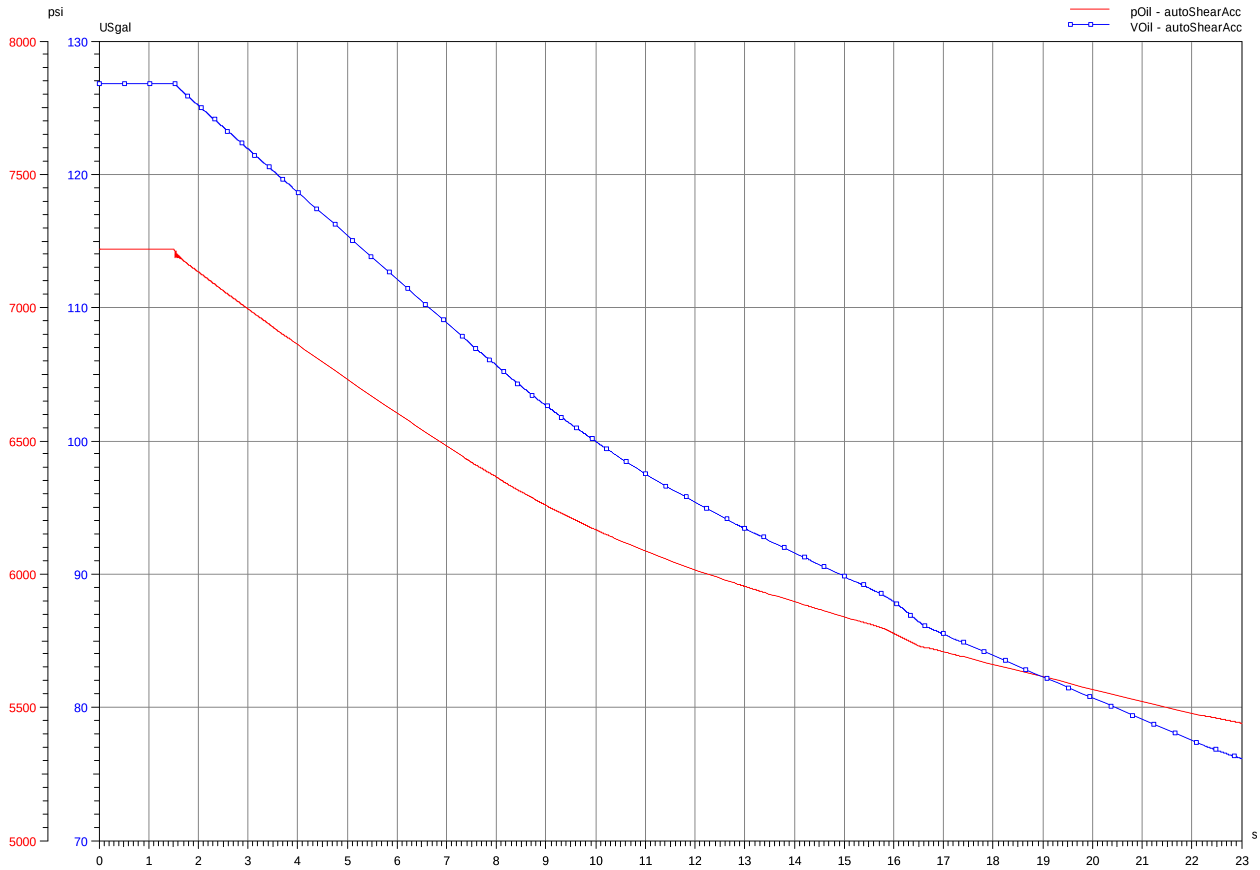


Figure 110) “Auto Shear” accumulator pressure and oil volume – Case 5-2

Legend:	Description	Unit
pOil - autoShearAcc	Pressure in “Auto Shear Accumulators”	psi
VOil - autoShearAcc	Oil volume in “Auto Shear Accumulators”	USgal

5.5.2.2 Leak rate Cv 1 and 1500 psi BOP bore pressure

There is reported a leakage in the ST-lock line in an internal leak review dated June 7, 2010. The leakage is reported to be “significant” and an ROV was not able to build up pressure with a pump supplying 8 USgal/min.

The model is set up with 1500 psi BOP bore pressure a leakage in the ST-Lock shuttle valve connection. The leakage is modelled as a sharp edge orifice with a Cv of 1. Figure 111) shows the flow through the leak orifice as function of the pressure difference across the orifice.

Maximum flow is found to be 35.5 USgal/min at pressure difference of 1280 psi.

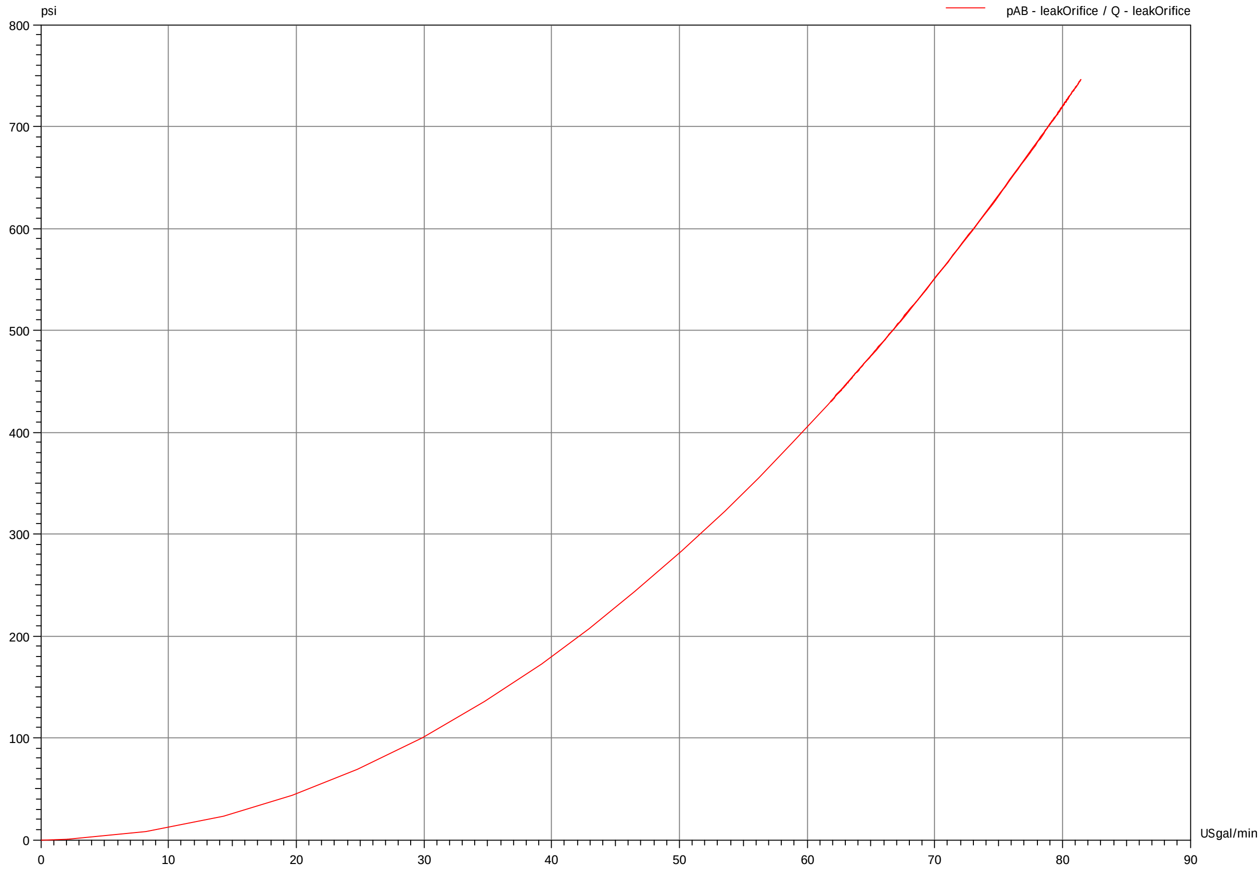


Figure 111) Leak Flow in the ST-Lock line – Case 5-3

Legend:	Description	Unit
pAB - leakOrifice	Pressure difference across the orifice	psi
Q – leakOrifice	Flow through the leak orifice.	USgal/min

Figure 112) shows the BSR actuator and ST Lock strokes together with the BSR Open and Close pressures for actuator 1 when closing and cutting drill pipe at 5000 meter water depth, 1500 psi in the BOP bore and a leakage in the ST-Lock line.

The actuator starts to close at 1.5 seconds. The V-knife reaches the pipe at 7.5 seconds and the pressure builds up until it is enough to start squeezing the pipe.

At 10.8 seconds, the V-knife start to shear the pipe and at 11.9 seconds it is through the pipe and the ST Lock starts to close.

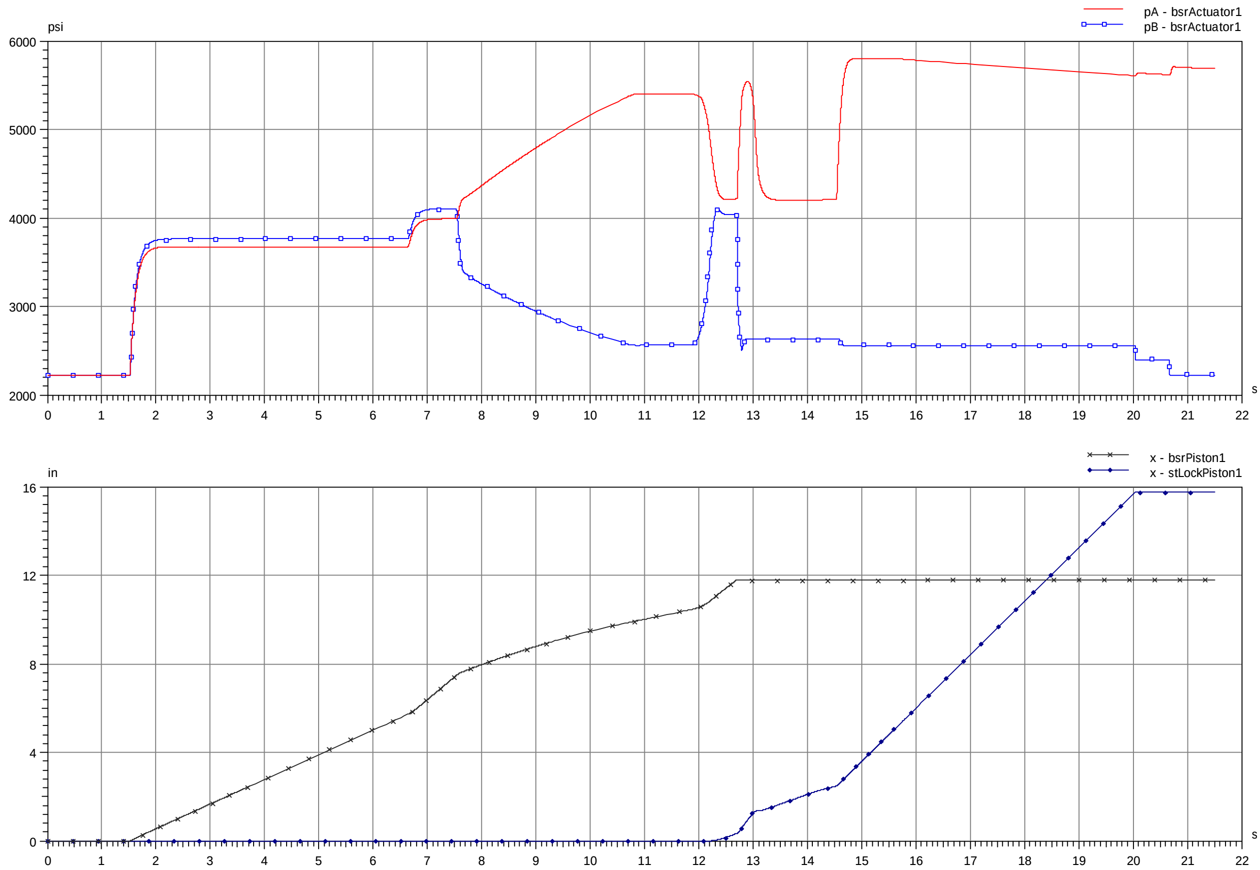


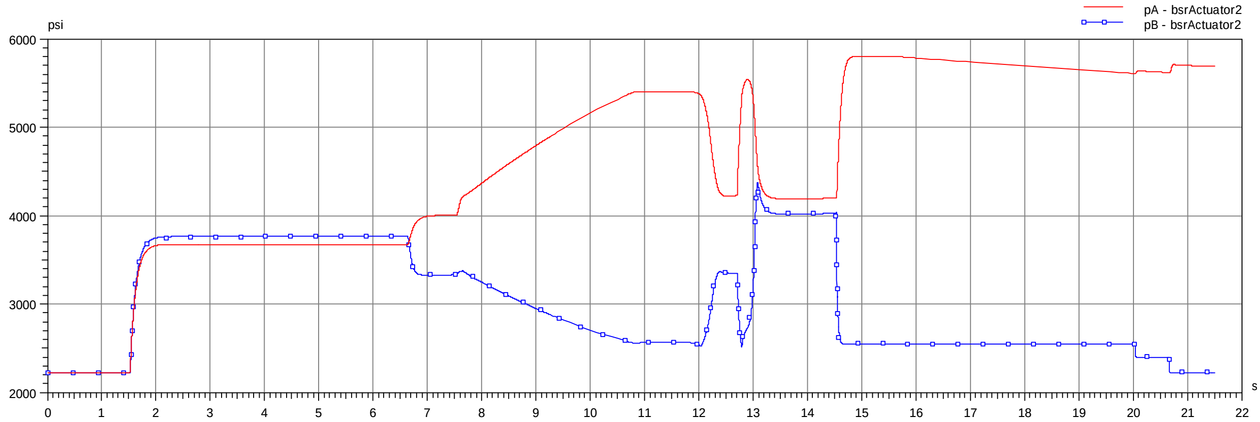
Figure 112) Actuator 1 Open/close pressure and actuator position – Case 5-3

Legend:	Description	Unit
pA – bsrActuator1	Pressure in BSR actuator 1 Close cavity	psi
pB – bsrActuator1	Pressure in BSR actuator 1 Open cavity	psi
x – bsrPiston1	BSR actuator 1 piston position	in
x – stLockPiston1	ST Lock position	in

Figure 113) shows the BSR actuator and ST Lock strokes together with the BSR Open and Close pressures for actuator 2 when closing and cutting drill pipe at 5000 meter water depth, 1500 psi in the BOP bore and a leakage in the ST-Lock line.

The actuator starts to close at 1.5 seconds. The flat knife reaches the pipe at 6.6 seconds and the stroke stops until 7.5 seconds when Actuator 1 has reached the pipe. The pressure builds up in parallel with Actuator 1 and both actuators starts to cut the pipe at 10.8 seconds.

Actuator 1 is through the pipe walls at 11.9 seconds. At this point, actuator 2 stops until actuator 1 reaches its end stop and pressure can build up again. At 12.9 second is also Actuator 2 through the pipe walls and moves fast to its end stop.



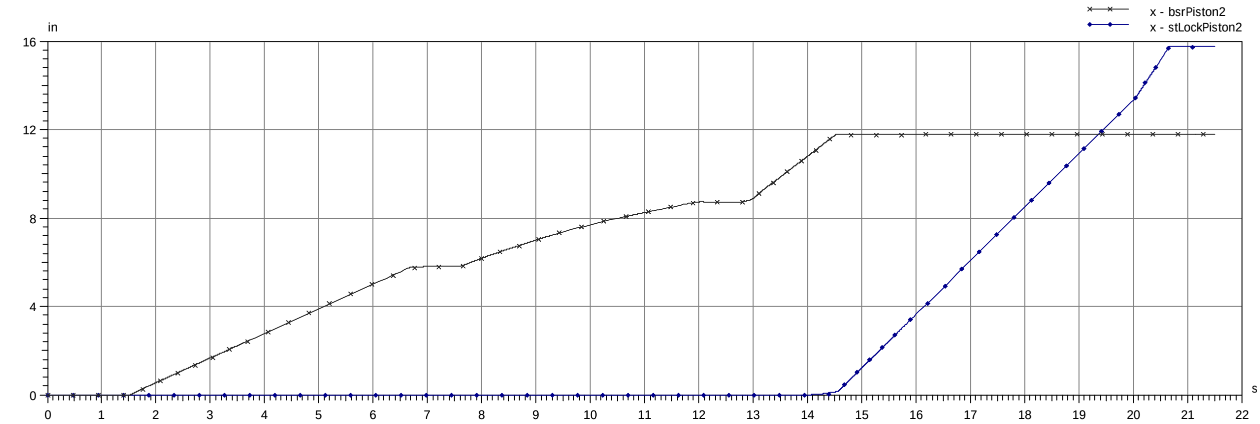


Figure 113) Actuator 2 Open/close pressure and actuator position – Case 5-3

Legend:	Description	Unit
pA – bsrActuator2	Pressure in BSR actuator 2 Close cavity	psi
pB – bsrActuator2	Pressure in BSR actuator 2 Open cavity	psi
x – bsrPiston2	BSR actuator 2 piston position	in
x – stLockPiston2	ST Lock position	in

As can be seen from the pressure and volume trend plot in Figure 114), the leakage causes a continuously loss of hydraulic fluid as soon as the “Auto Shear” function is activated.

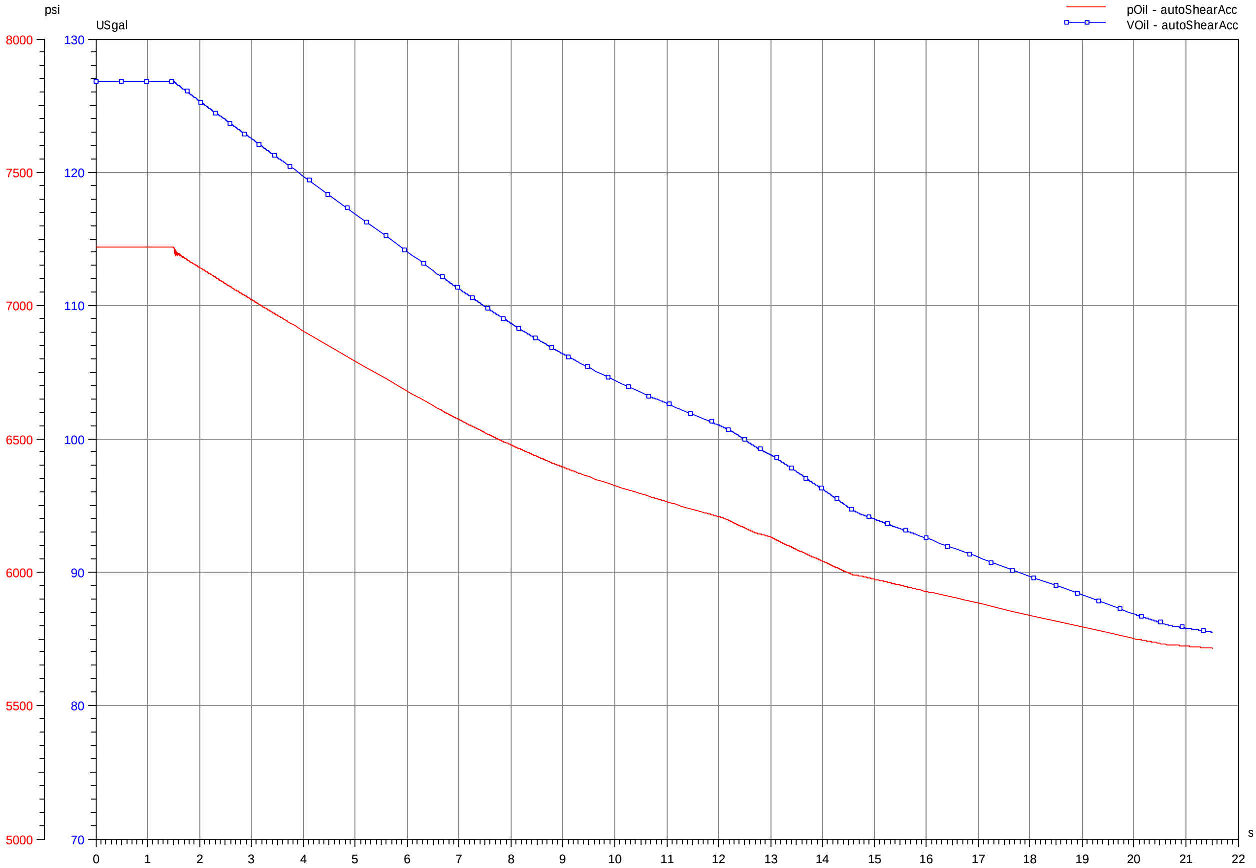


Figure 114) “Auto Shear” accumulator pressure and oil volume – Case 5-3

Legend:	Description	Unit
pOil - autoShearAcc	Pressure in “Auto Shear Accumulators”	psi
VOil - autoShearAcc	Oil volume in “Auto Shear Accumulators”	USgal

5.5.2.3 Leak Rate Cv 3 and 3000 psi BOP bore pressure

The model is set up with a leakage in the ST-Lock shuttle valve connection. The leakage is modelled as a sharp edge orifice with a Cv of 3. Figure 115) shows the flow through the leak orifice as function of the pressure difference across the orifice.

Maximum flow is found to be 86.9 USgal/min at pressure difference of 850.3 psi.

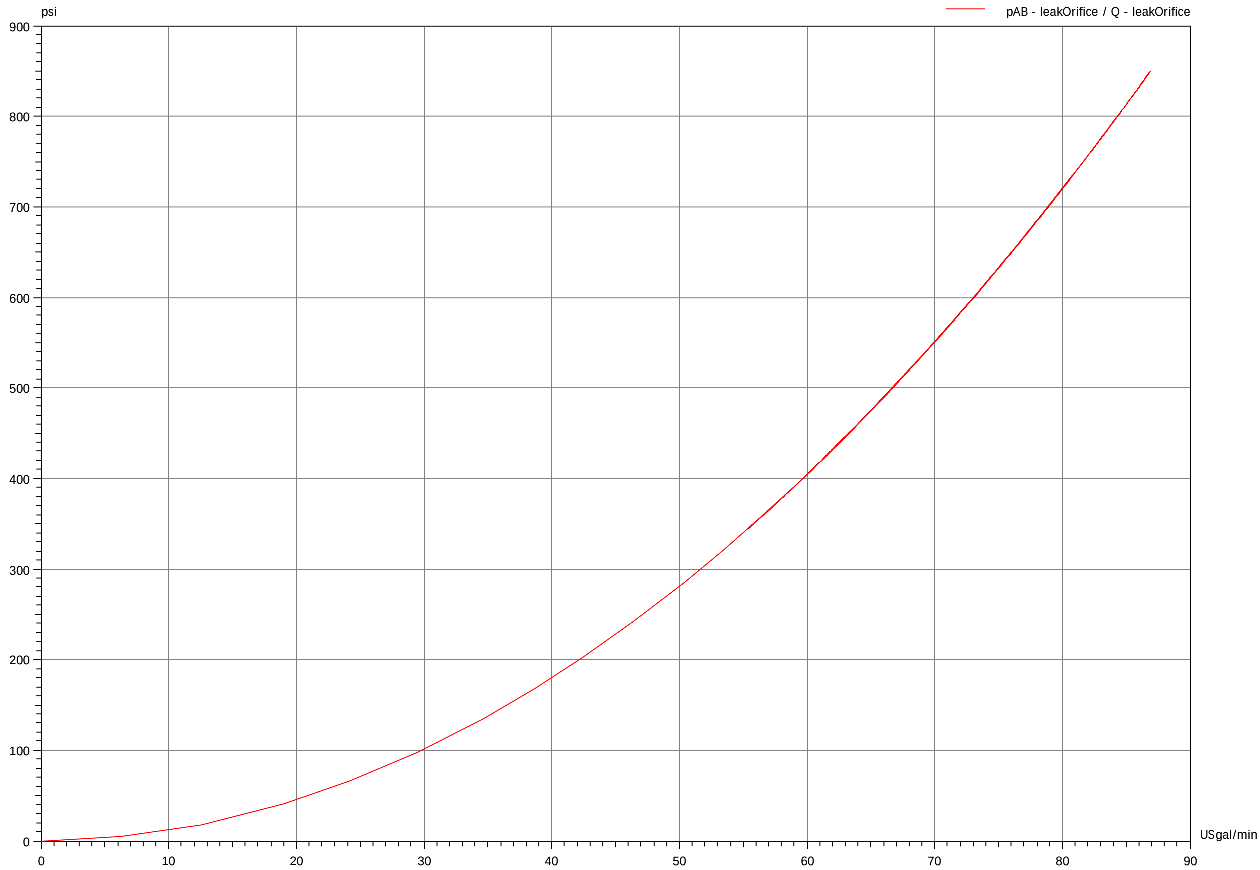


Figure 115) Leak Flow in the ST-Lock line – Case 5-4

Legend:	Description	Unit
pAB - leakOrifice	Pressure difference across the orifice	psi
Q – leakOrifice	Flow through the leak orifice.	USgal/min

Figure 116) shows the BSR actuator and ST Lock strokes together with the BSR Open and Close pressures for actuator 1 when closing and cutting drill pipe at 5000 meter water depth, 3000 psi in the BOP bore and a leakage in the ST-Lock line.

The actuator starts to close at 1.5 seconds. The V-knife reaches the pipe at 8.1 seconds and the pressure builds up until it is enough to start squeezing the pipe.

At 12.4 seconds, the V-knife start to shear the pipe and at 14 seconds it is through the pipe and the ST Lock starts to close.

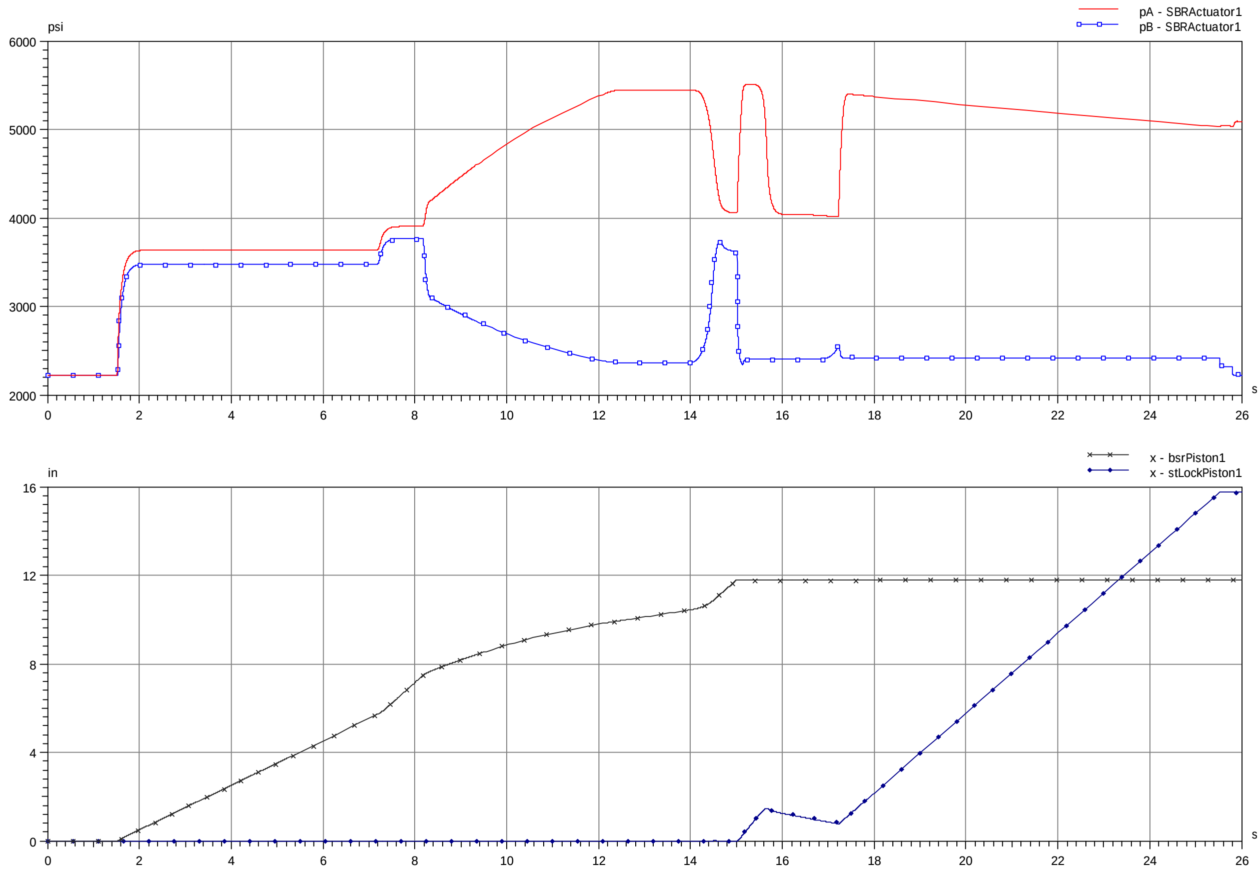


Figure 116) Actuator 1 Open/close pressure and actuator position – Case 5-4

Legend:	Description	Unit
pA – bsrActuator1	Pressure in BSR actuator 1 Close cavity	psi
pB – bsrActuator1	Pressure in BSR actuator 1 Open cavity	psi
x – bsrPiston1	BSR actuator 1 piston position	in
x – stLockPiston1	ST Lock position	in

Figure 117) shows the BSR actuator and ST Lock strokes together with the BSR Open and Close pressures for actuator 2 when closing and cutting drill pipe at 5000 meter water depth, 3000 psi in the BOP bore and a leakage in the ST-Lock line.

The actuator starts to close at 1.5 seconds. The flat knife reaches the pipe at 7.2 seconds and the stroke stops until 8.1 seconds when Actuator 1 has reached the pipe. The pressure builds up in parallel with Actuator 1 and both actuators starts to shear the pipe at 12.4 seconds.

Actuator 1 is through the pipe walls at 14 seconds. At this point, actuator 2 stops until actuator 1 reaches its end stop and pressure can build up again. At 15.4 second is also Actuator 2 through the pipe walls and moves fast to its end stop.

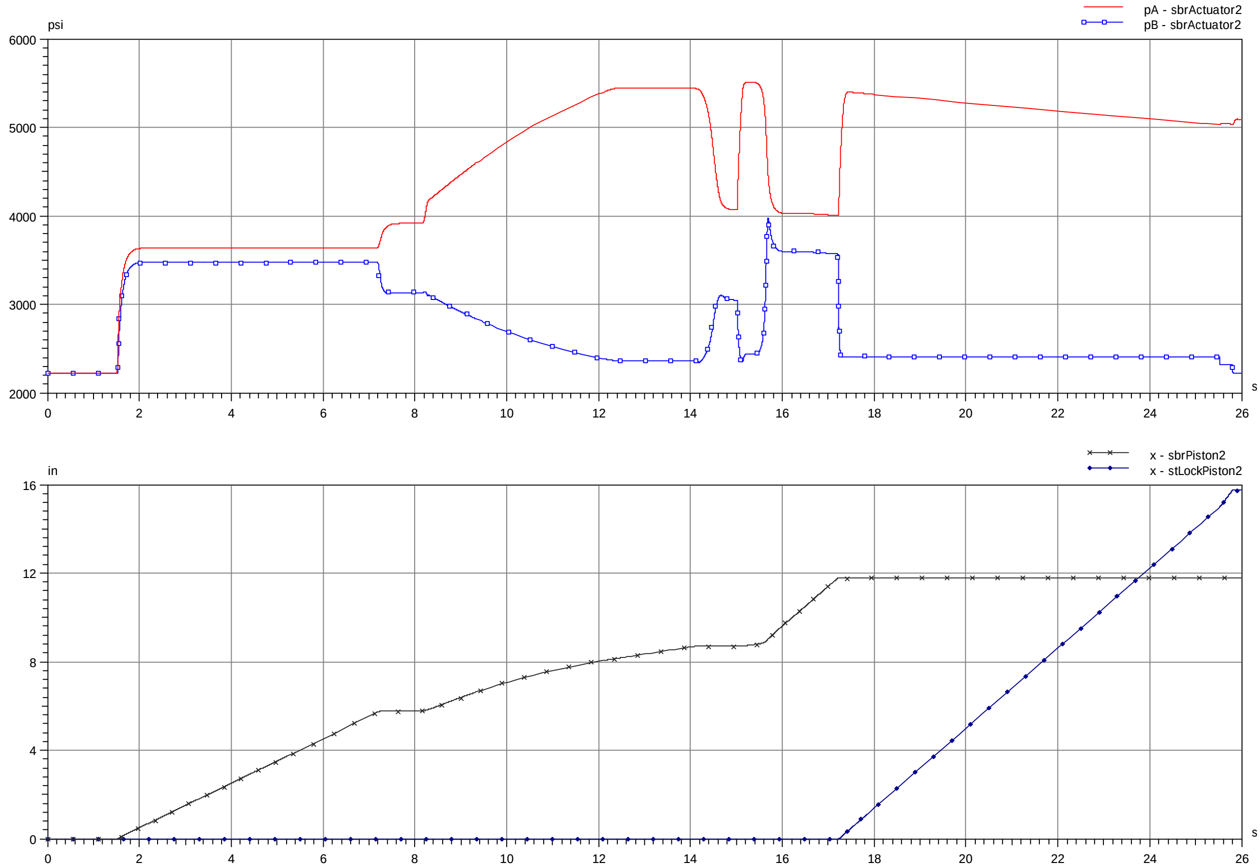


Figure 117) Actuator 2 Open/close pressure and actuator position – Case 5-4

Legend:	Description	Unit
pA – bsrActuator2	Pressure in BSR actuator 2 Close cavity	psi
pB – bsrActuator2	Pressure in BSR actuator 2 Open cavity	psi
x – bsrPiston2	BSR actuator 2 piston position	in
x – stLockPiston2	ST Lock position	in

As can be seen from the pressure and volume trend plot in Figure 118), the leakage causes a continuously loss of hydraulic fluid as soon as the “Auto Shear” function is activated.

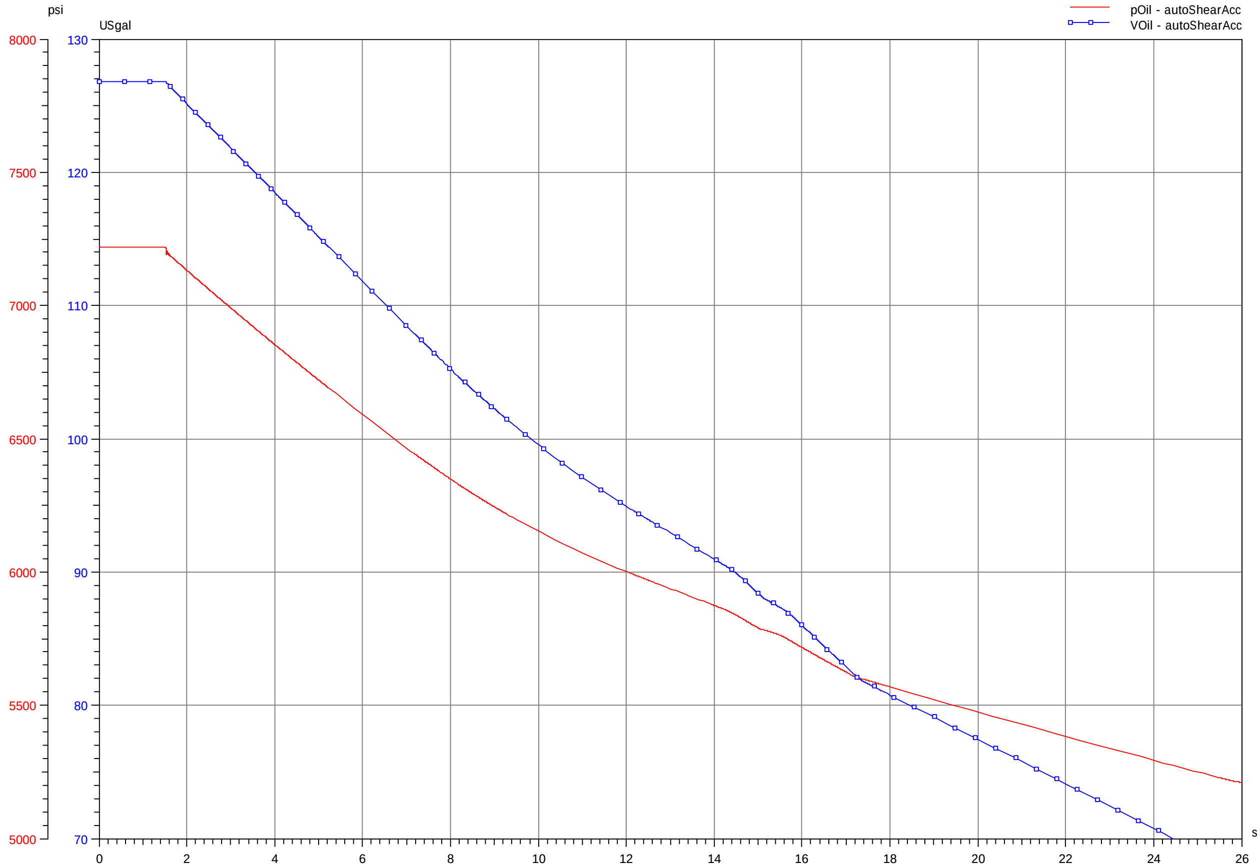


Figure 118) “Auto Shear” accumulator pressure and oil volume – Case 5-4

Legend:	Description	Unit
pOil - autoShearAcc	Pressure in “Auto Shear Accumulators”	psi
VOil - autoShearAcc	Oil volume in “Auto Shear Accumulators”	USgal

5.6 Scenario 6 – Additional simulations

This section contains additional simulation cases performed on different circuits under special conditions.

The cases described in this scenario are as follows:

Case 6-1: Closing one annular preventer with 8200 psi BOP bore pressure.

Case 6-2: Closing one annular preventer with 2500 psi BOP bore pressure increasing to 3500 psi.

Case 6-3: Closing one annular preventer with 2500 psi BOP bore pressure increasing to 8200 psi.

5.6.1 Case 6-1: Closing one annular preventer with 8200 psi BOP bore pressure.

Solenoid valve no. 12 is energized at t=2 seconds and the 3-way pilot valves shift to "open" 1.4 seconds later (at t=3.4 s). As can be seen in Figure 119), the annular preventer will not start to close with 1500 psi closing pressure and 8200 psi in the BOP bore.

The actuator closing ratio is 8.7:1. With a BOP bore pressure of 8200 psi, the resulting effective available pressure to compress the packer element with 1500 psi closing pressure is 1500 psi - (8200 psi /8.7) = 557 psi. This is not enough to start to move the piston and compress the packer.

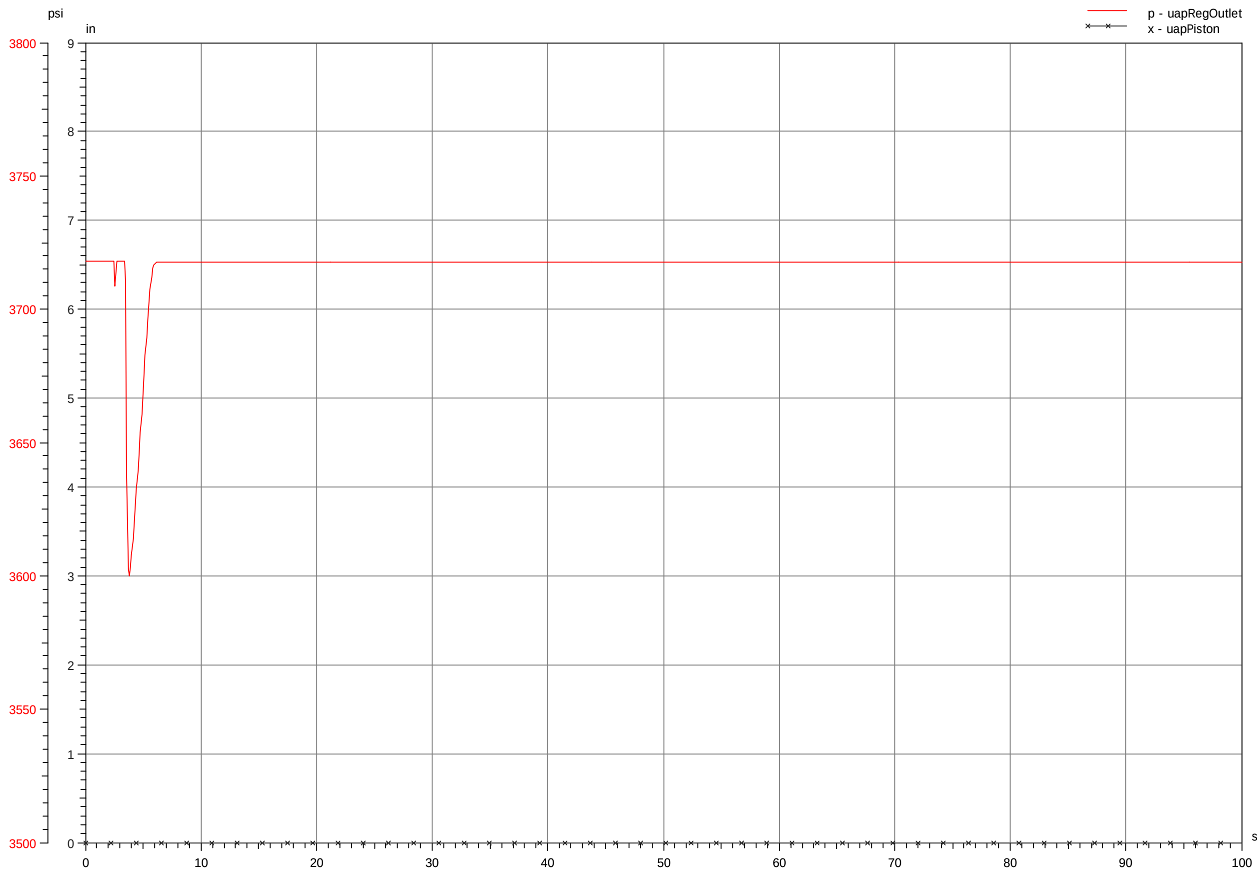


Figure 119) Regulated pressure (1500 psi) and annular preventer actuator pos. – Case 6-1

Legend:	Description	Unit
p - uapRegOutlet	Pressure down stream of the Upper Annular BOP pressure regulator	psi
x - uapPiston	Annular preventer actuator position	in

Figure 120) shows the same closing sequence as shown in previous figure but with 2000 psi closing pressure.

As can be seen, the preventer closes but it uses some 75 seconds on the closing sequence.

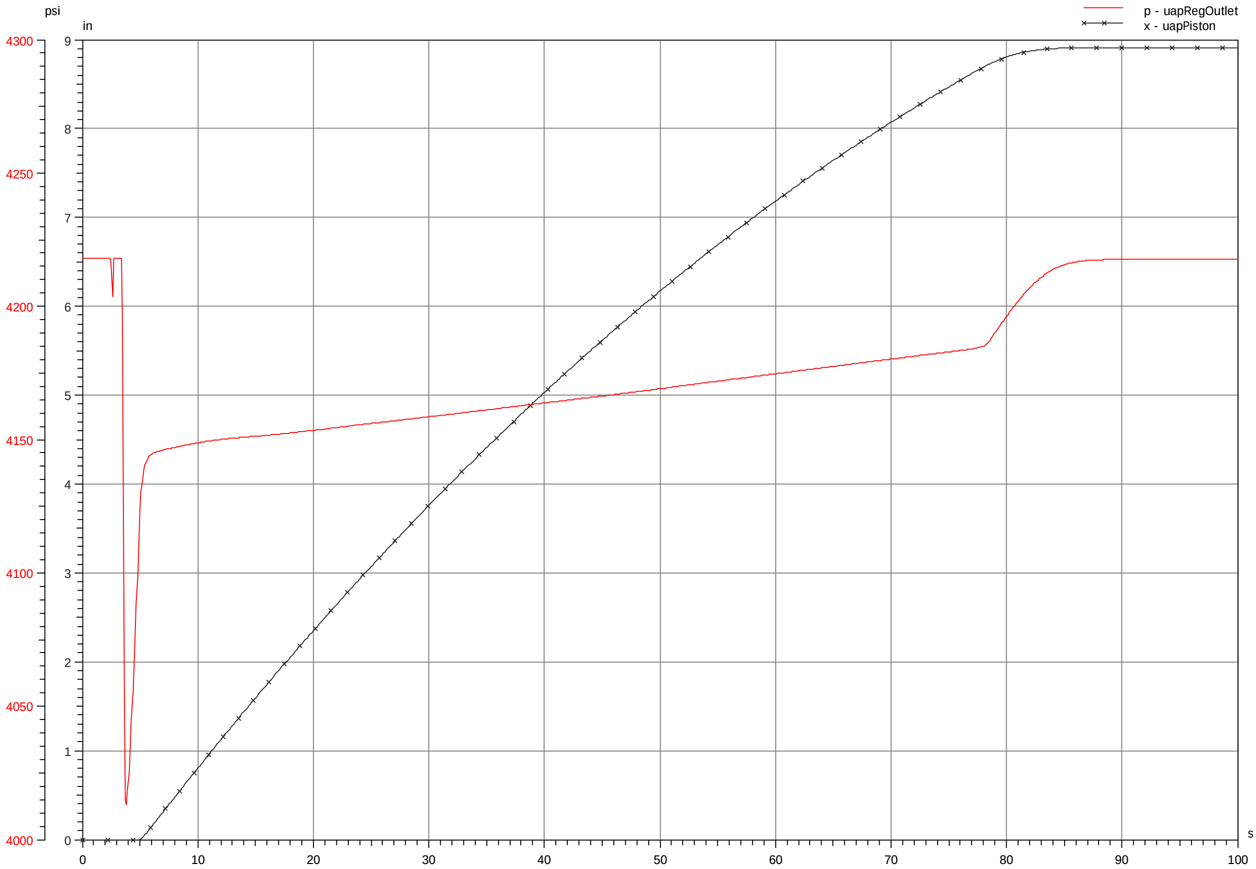


Figure 120) Regulated pressure (2000 psi) and annular preventer actuator pos. – Case 6-1

Legend:	Description	Unit
p - uapRegOutlet	Pressure down stream of the Upper Annular BOP pressure regulator	psi
x - uapPiston	Annular preventer actuator position	in

Figure 121) shows the same closing sequence as shown in previous figure but with 1700 psi closing pressure.

As can be seen, the preventer starts to close but are only able to stroke some 2.3 inches.

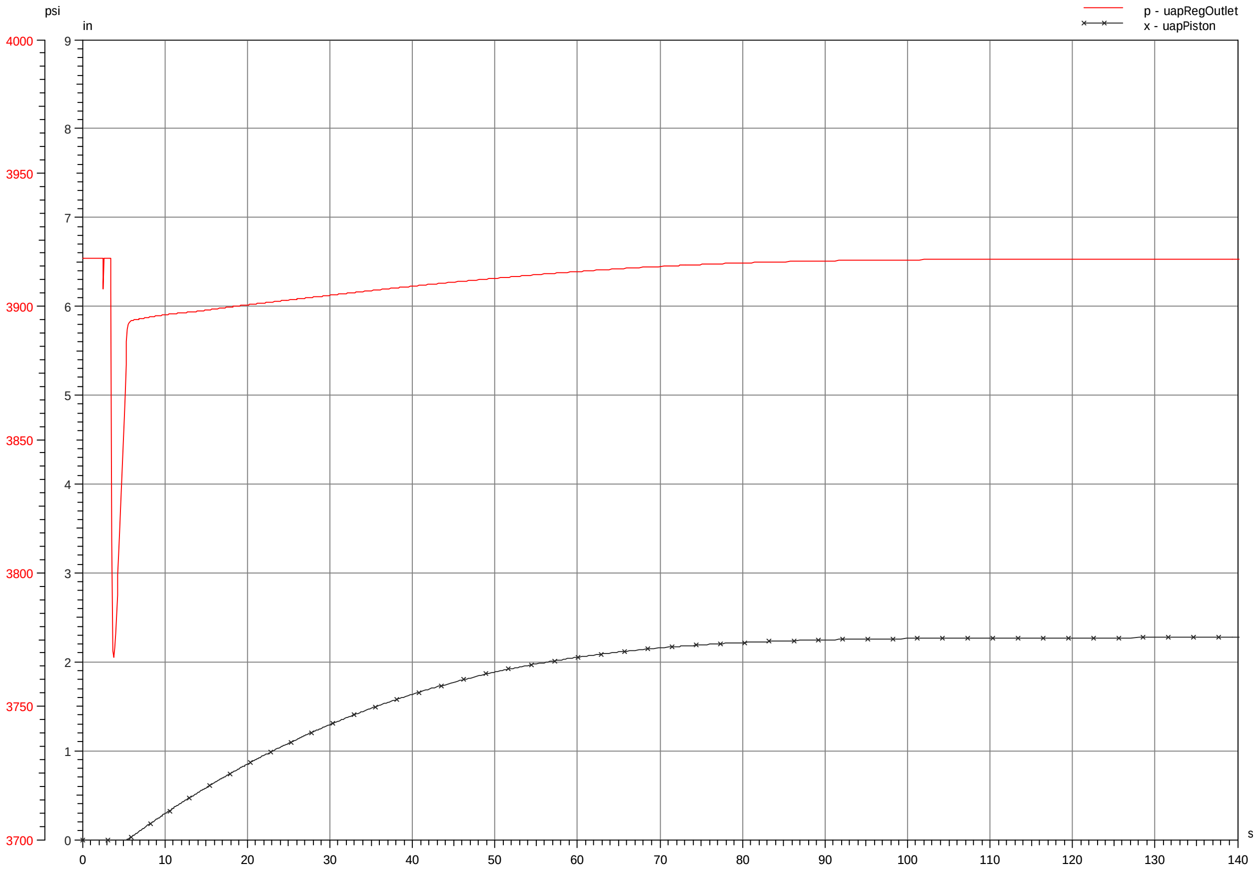


Figure 121) Regulated pressure (1700 psi) and annular preventer actuator pos. – Case 6-1

Legend:	Description	Unit
p - uapRegOutlet	Pressure down stream of the Upper Annular BOP pressure regulator	psi
x - uapPiston	Annular preventer actuator position	in

5.6.2 Case 6-2: Closing one annular preventer with 2500 psi BOP bore pressure increasing to 3500 psi.

Solenoid valve no. 12 is energized at t=2 seconds and the 3-way pilot valves shift to “open” 1.4 seconds later (at t=3.4 s). The closing time from “firing” solenoid valve 12 until the packer element reaches the pipe is simulated to be 30 seconds.

At t=30 seconds, the BOP bore pressure increase from 2500 psi to 3500 psi. This can be seen as a small increase in the regulated close pressure which is caused by the actuator area that is exposed to the BOP bore.

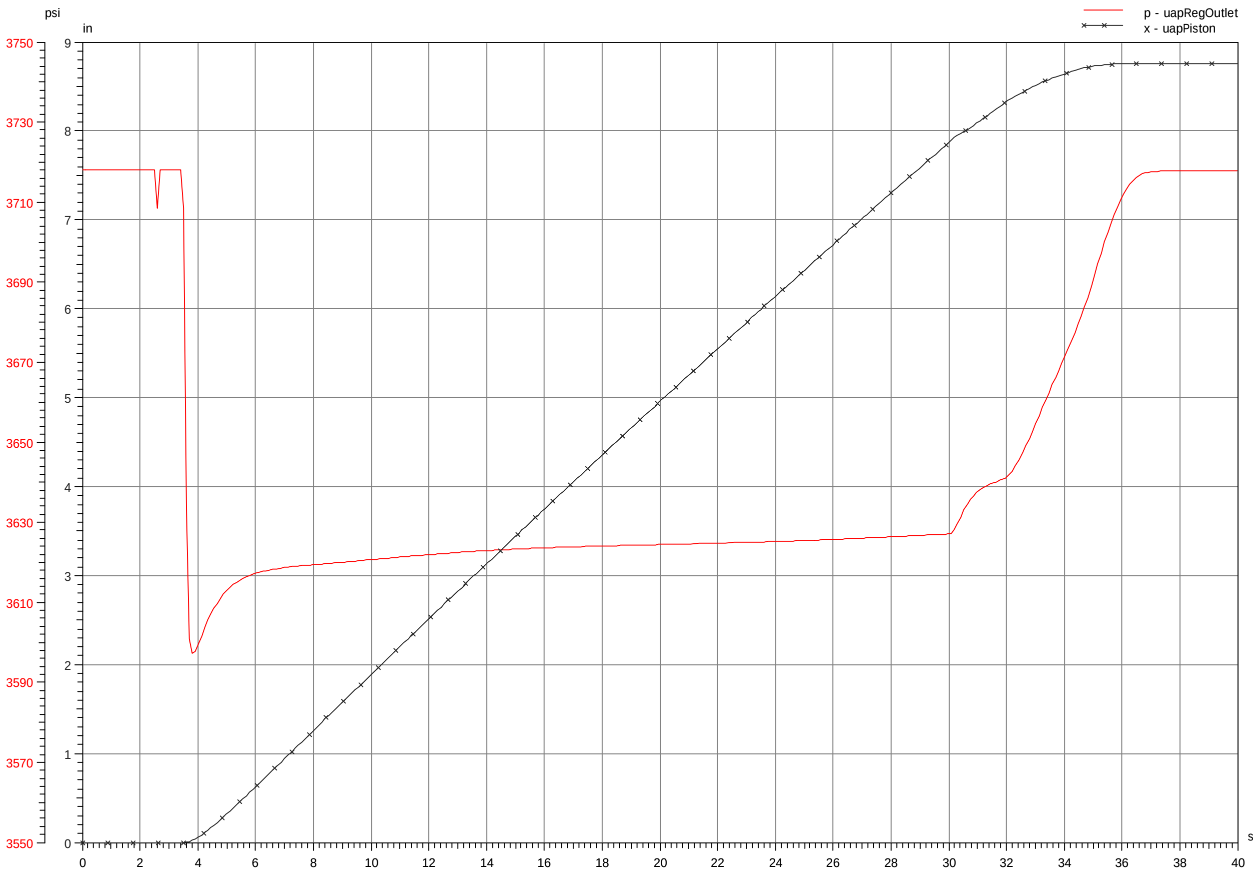


Figure 122) Regulated pressure (1500 psi) and annular preventer actuator pos. – Case 6-2

Legend:	Description	Unit
p - uapRegOutlet	Pressure down stream of the Upper Annular BOP pressure regulator	psi
x - uapPiston	Annular preventer actuator position	in

By increasing the closing pressure from 1500 psi to 1700 psi, the closing time is reduced approximately 2 seconds and the actuator strokes 0.08 inches longer due to the packer compression.

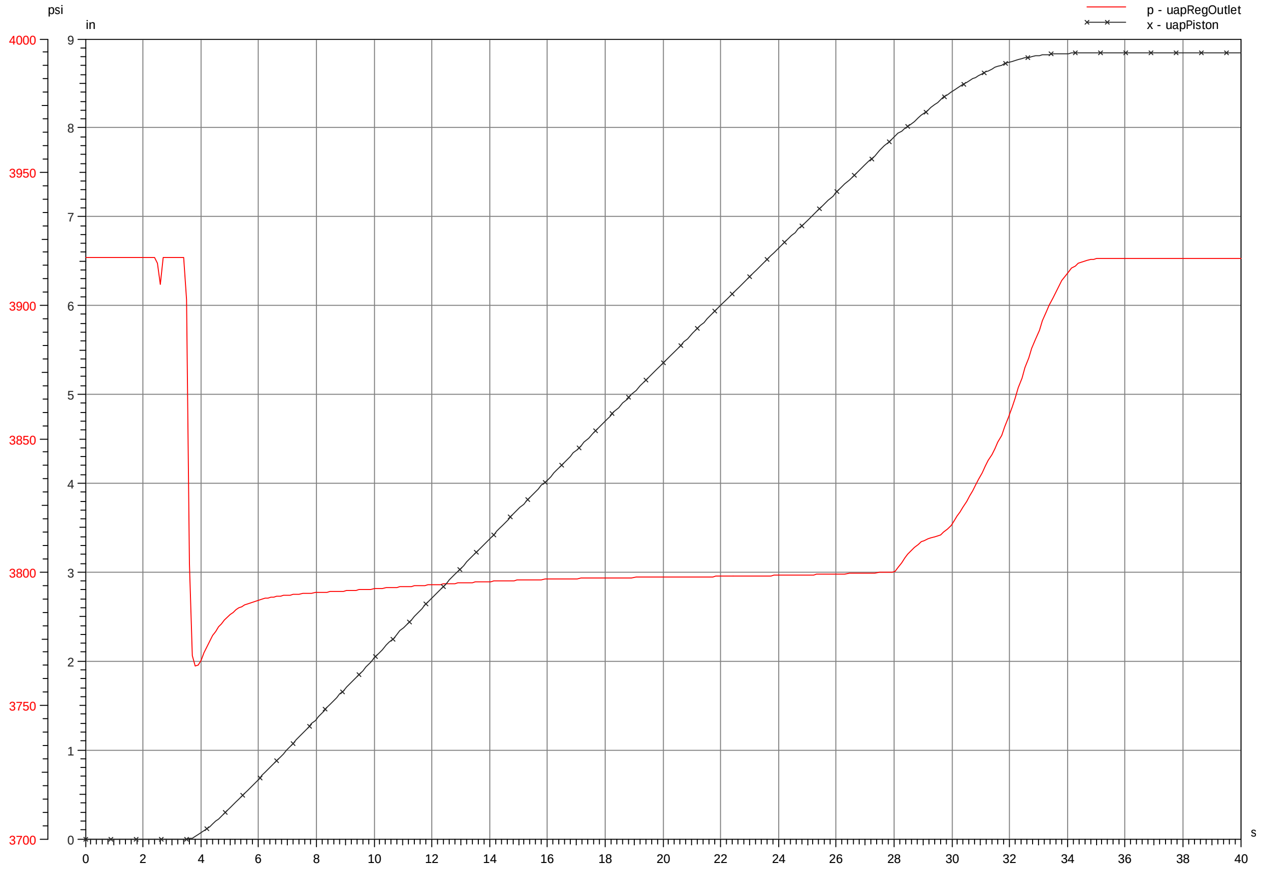


Figure 123) Regulated pressure (1700 psi) and annular preventer actuator pos. – Case 6-2

Legend:	Description	Unit
p - uapRegOutlet	Pressure down stream of the Upper Annular BOP pressure regulator	psi
x - uapPiston	Annular preventer actuator position	in

5.6.3 Case 6-3: Closing one annular preventer with 2500 psi BOP bore pressure increasing to 8200 psi.

Solenoid valve no. 12 is energized at t=2 seconds and the 3-way pilot valves shift to "open" 1.4 seconds later (at t=3.4 s). As can be seen, as soon as the BOP bore pressure increases (at t=26.5 seconds), the actuator stroke stops.

The annular preventer will not close with 1700 psi closing pressure when BOP bore pressure is 8200 psi.

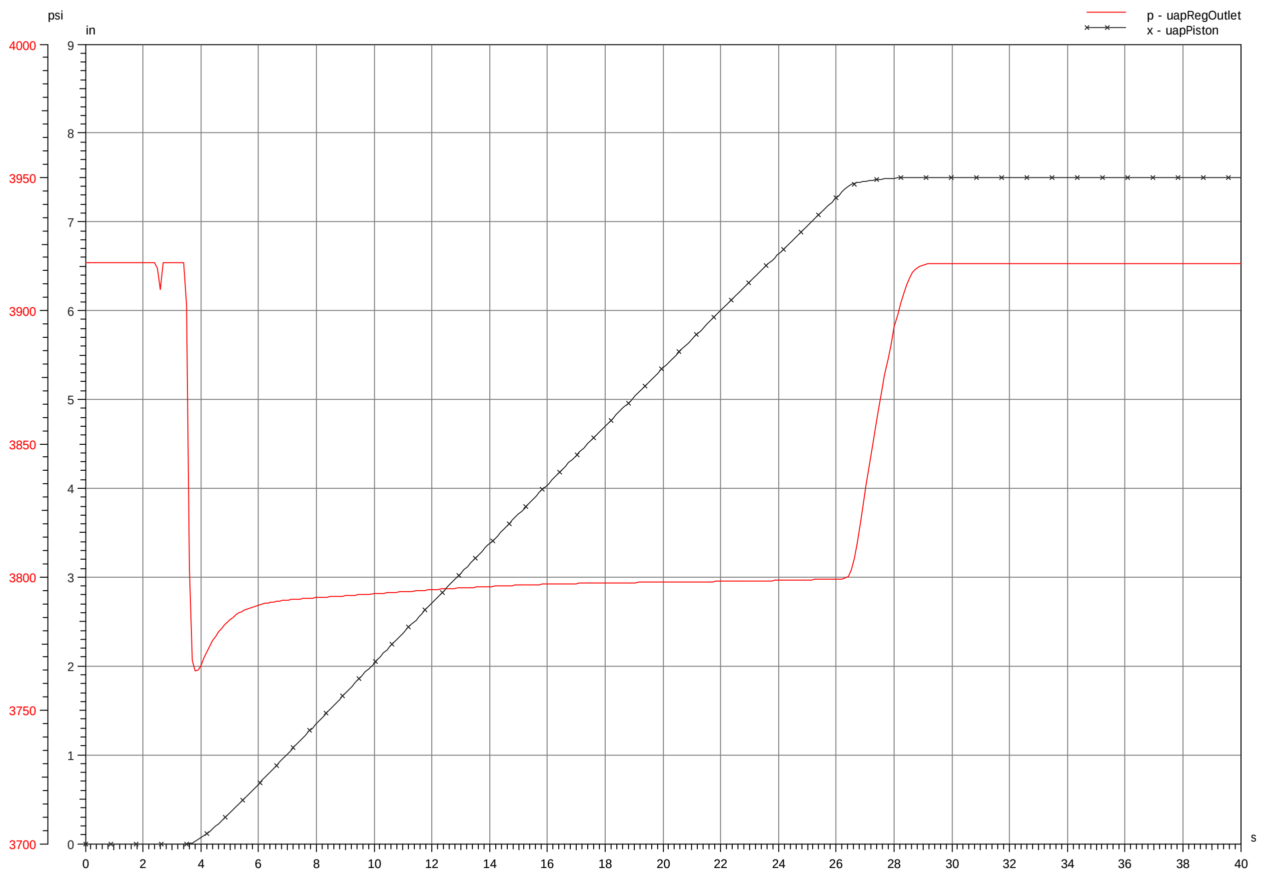


Figure 124) Regulated pressure (1700 psi) and annular preventer actuator pos. – Case 6-3

Legend:	Description	Unit
p - uapRegOutlet	Pressure down stream of the Upper Annular BOP pressure regulator	psi
x - uapPiston	Annular preventer actuator position	in

By increasing the closing pressure from 1700 psi to 2000 psi, the annular preventer will close. As can be seen in Figure 125), the BOP bore pressure is increased at 24 seconds resulting in a reduction in the annular preventer close velocity. The annular preventer will be fully closed at approximately 46 seconds.

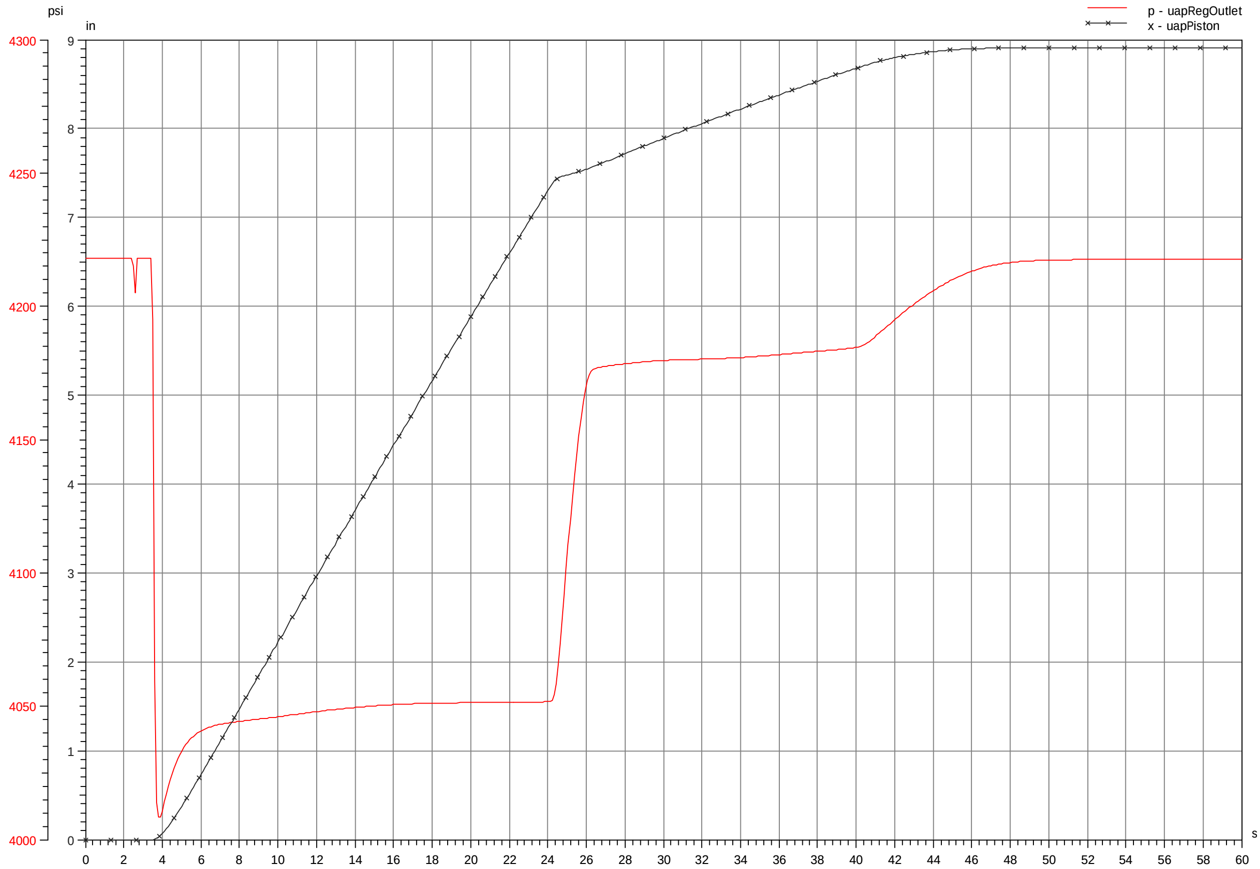


Figure 125) Regulated pressure (2000 psi) and annular preventer actuator pos. – Case 6-3

Legend:	Description	Unit
p - uapRegOutlet	Pressure down stream of the Upper Annular BOP pressure regulator	psi
x - uapPiston	Annular preventer actuator position	in

6 APPENDIX

Appendix I: Agito LST-0019

PARAMETER LIST
DEEPWATER HORIZON BOP CONTROL SYSTEM
ULTRA DEEP

2	12.08.2010	Snorre Barlindhaug	Rune Lien	Rune Lien	Released with updates
1	14.07.2010	Rune Lien	Svein Myhra	Rune Lien	Released with updates
-	01.07.2010	Rune Lien	Roger Berg	Rune Lien	First Release
Rev.	**Date**	**Author**	**Check**	**Approval**	**Change Description**

Table of Contents

1 INTRODUCTION

This document defines the input parameters for the hydraulic analysis models for the Deep Water Horizon BOP system

The hydraulic analysis is given in Agito report Doc REP-0038

1.1 Scope

The scope of this document is to define the simulation cases and to specify the input parameters used in the hydraulic analysis. All parameters are cross-referenced to the sources.

1.2 Applicable Documents

The input parameters are found in the project documentation given by Customer. Further clarifications are given in meetings and e-mail communications. All input parameters listed in this document are cross-referenced to the sources. Estimated parameters are identified.

1.3 Abbreviations

The following abbreviations are used in this document:

Abbreviation	Description
BOP	Blow Out Preventer
HPU	Hydraulic Power Unit
ID	Internal Diameter
LMRP	Lower Marine Riser Package
OD	Outer Diameter
RAM	Rigid Armed Mooring
VBR	Variable Bore RAM

1.4 Revision History

Revision no.	Descriptions of changes
Revision -	First release. Issued with some “open” parameters.
Revision 1	The following changes has been made for this revision: • 1” Hot Line Supply is only active during installation of BOP and is taken out of the model. • Included end fittings on hoses • Included the VBR (section 4.10) • Changed Cv value for annular preventer pressure regulator from 10.6 to 30. (section 4.8) • Changed Cv value for annular preventer 3-way control valve from 10.4 to 30. (section 4.8) • Included Cv value for VBR 4-way control valve Cv=30. (section 4.8) • Specified better the scenarios/cases to be simulated • Changed the document title for better project identification.
Revision 2	The following changes has been made for this revision: • Included lines 65, 66, 67 and 68 in schematic for Elector-Hydraulic Control Pod. (4.7) • Changed heading form Hydraulic Control Pod (4.8) • Included schematic “Hydraulic Control Pod – Variable Bore Ram”(4.10) • Changed Variable Bore Ram form 4.10

2 SYSTEM DESCRIPTION

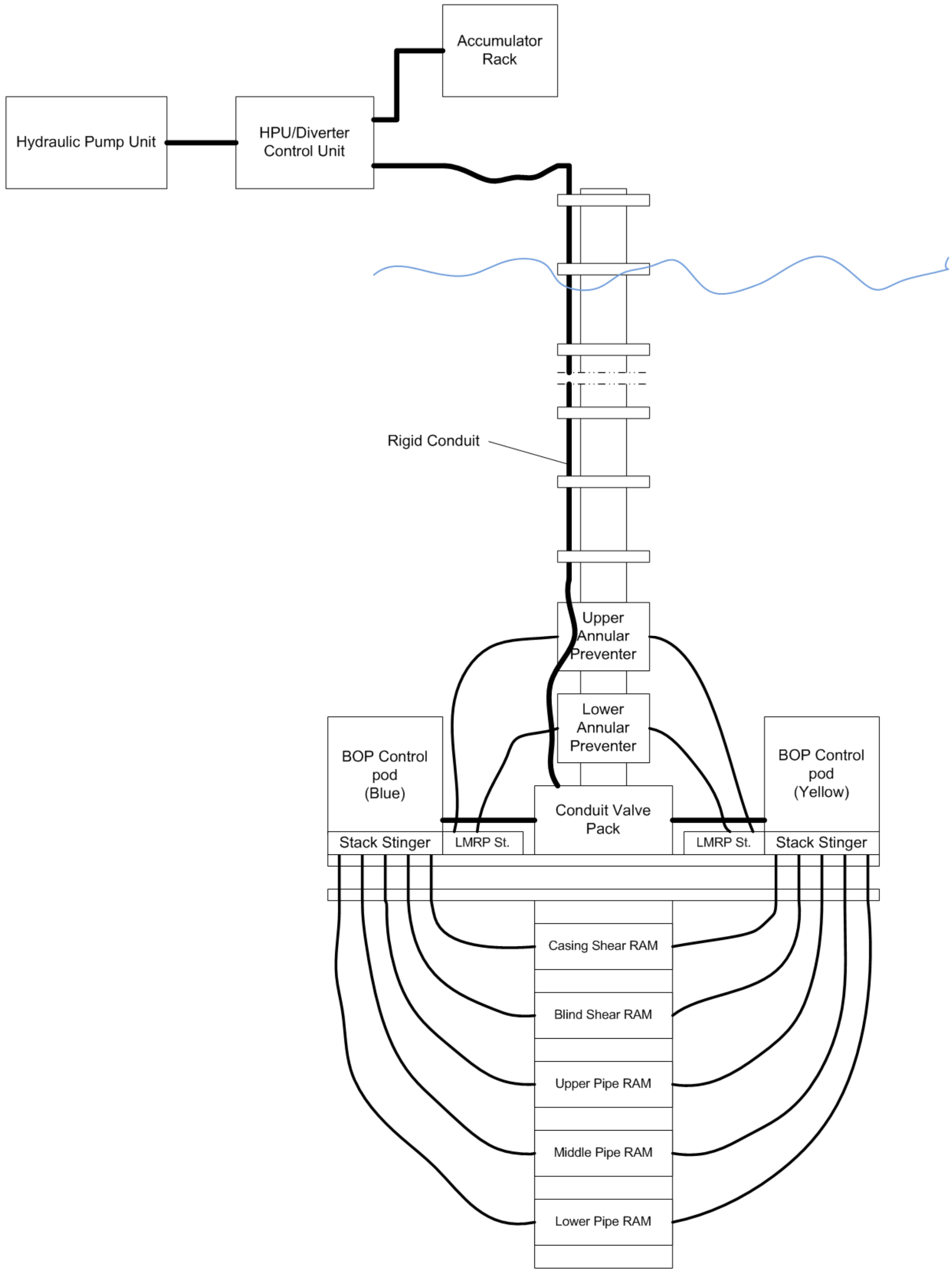


Figure 1. System Sketch

Figure 1 shows a sketch of the system that shall be modelled. The system is a traditionally BOP control system with surface pump and accumulator units, dual control Pod's and large valve actuators.

3 INITIAL CASES FOR SIMULATION

The simulation work is divided in to four different scenarios with separate sub cases for each scenario.

3.1 Scenario 1: Parallel operations of specified system

Case No.	Description	Results of interest
Case 1-1	Normal operation of one Annular Preventer at 5000 feet water depth and operation pressure of 1500 psi.	Verify model parameters up against test results from the real system.
Case 1-2	One Annular Preventer closed at 1500 psi. Increase the pressure to 2000 psi.	Required time for pressure increase.
Case 1-3	One Annular Preventer closed at 1500 psi. Close the second Annular Preventer.	Pressure variation in the close cavity of the first closed preventer.
Case 1-4	One Annular Preventer closed at 1500 psi. Close the second Annular Preventer together with one VBR.	Pressure variation in the close cavity of the first closed preventer.
Case 1-5	One Annular Preventer closed at 1500 psi. Close the second Annular Preventer together with two VBR's.	Pressure variation in the close cavity of the first closed preventer.

3.2 Scenario 2: Parallel operations with reduced LMRP accumulator capacity

Case No.	Description	Results of interest
Case 2-1	One Annular Preventer closed at 1500 psi. Close the second Annular Preventer.	Pressure variation in the close cavity of the first closed preventer.
Case 2-2	One Annular Preventer closed at 1500 psi. Close the second Annular Preventer together with one VBR.	Pressure variation in the close cavity of the first closed preventer.
Case 2-3	One Annular Preventer closed at 1500 psi. Close the second Annular Preventer together with two VBR's.	Pressure variation in the close cavity of the first closed preventer.

All cases in scenario 2 shall be simulated with a) reduced pre-charge pressure and b) correct pre-charge pressure but with reduced accumulator volume (one bottle out of gas)

3.3 Scenario 3: Parallel operations with high BOP pressure

Case No.	Description	Results of interest
Case 3-1	One Annular Preventer closed at 1500 psi. Close the second Annular Preventer.	Pressure variation in the close cavity of the first closed preventer.
Case 3-2	One Annular Preventer closed at 1500 psi. Close the second Annular Preventer together with one VBR.	Pressure variation in the close cavity of the first closed preventer.
Case3-3	One Annular Preventer closed at 1500 psi. Close the second Annular Preventer together with two VBR's.	Pressure variation in the close cavity of the first closed preventer.

Well pressure build-up shall be included to replicate the real conditions as close as possible.

3.4 Scenario 4: Parallel operations with leakage in annular preventer close line

Case No.	Description	Results of interest
Case 4-1	One Annular Preventer closed at 1500 psi. Close the second Annular Preventer.	Pressure variation in the close cavity of the first closed preventer.
Case 4-2	One Annular Preventer closed at 1500 psi. Close the second Annular Preventer together with one VBR.	Pressure variation in the close cavity of the first closed preventer.
Case4-3	One Annular Preventer closed at 1500 psi. Close the second Annular Preventer together with two VBR's.	Pressure variation in the close cavity of the first closed preventer.

All cases in scenario 4 shall be simulated with a) leakage equal to surface pump capacity and b) 25% above maximum pump capacity.

4 PARAMETERS

4.1 Global Parameters

Description	Value	Unit	Reference
Water Depth	5000	feet	Meeting 06/24/10
Type of fluid	Tap water mixture		Meeting 06/23/10
Subsea Temperature	4	ºC	Meeting 06/26/10

4.2 Pump Unit

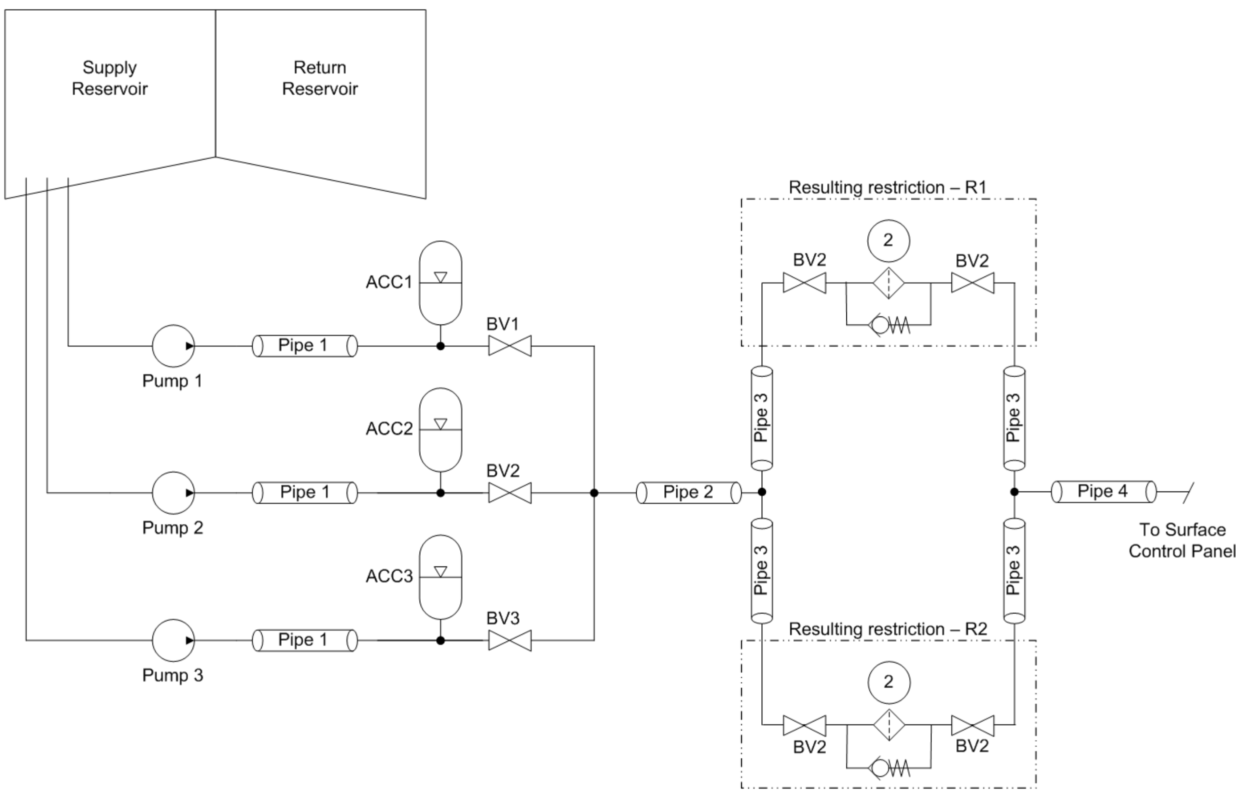


Figure 2. Surface HPU Model Schematics

Description	Value	Unit	Reference
Pump 1			
Pump Flow	25	USgal/min	Meeting 06/23/10
Start pressure:	4600	psi	Meeting 06/24/10
Stop pressure :	5000	psi	Meeting 06/24/10
Pump 2			
Pump Flow	25	USgal/min	Meeting 06/23/10
Start pressure:	4400	psi	Meeting 06/24/10
Stop pressure :	5000	psi	Meeting 06/24/10
Pump 3			
Pump Flow	25	USgal/min	Meeting 06/23/10
Start pressure:	4200	psi	Meeting 06/24/10
Stop pressure :	5000	psi	Meeting 06/24/10
Pipe 1:			Flow Diagram
ID 1.9" OD x 0.4 WT	1.1	inch	Drawing number SK-122160-21-05
Length:	3	m	Length estimated
Pipe 2:			Flow Diagram
ID 2.575" OD x 0.436 WT	1.503	inch	Drawing number SK-122160-21-05
Length:	4	m	Length estimated
Pipe 3:			Flow Diagram
ID 1.9" OD x 0.4 WT	1.1	inch	Drawing number SK-122160-21-05
Length:	2	m	Length estimated
Pipe 4:			Flow Diagram
ID 2.575" OD x 0.436 WT	1.503	Inch	Drawing number SK-122160-21-05
Length:	1	m	Length estimated
BV1 to 3			
Cv (1 ½" ID)	260	-	Note 1:
BV2			
Cv (1 ½" ID)	260	-	Note 1:
Filter			
Cv	350	-	Estimated
Resulting Cv 1 and 2 (used in model):			
Cv	162	-	Calculated

Note 1: The estimated Cv values for the ball valves is found on the following web page: www.engineeringtoolbox.com/ball-valves-flow-coefficients-d_223.html

4.3 Diverter Control Unit

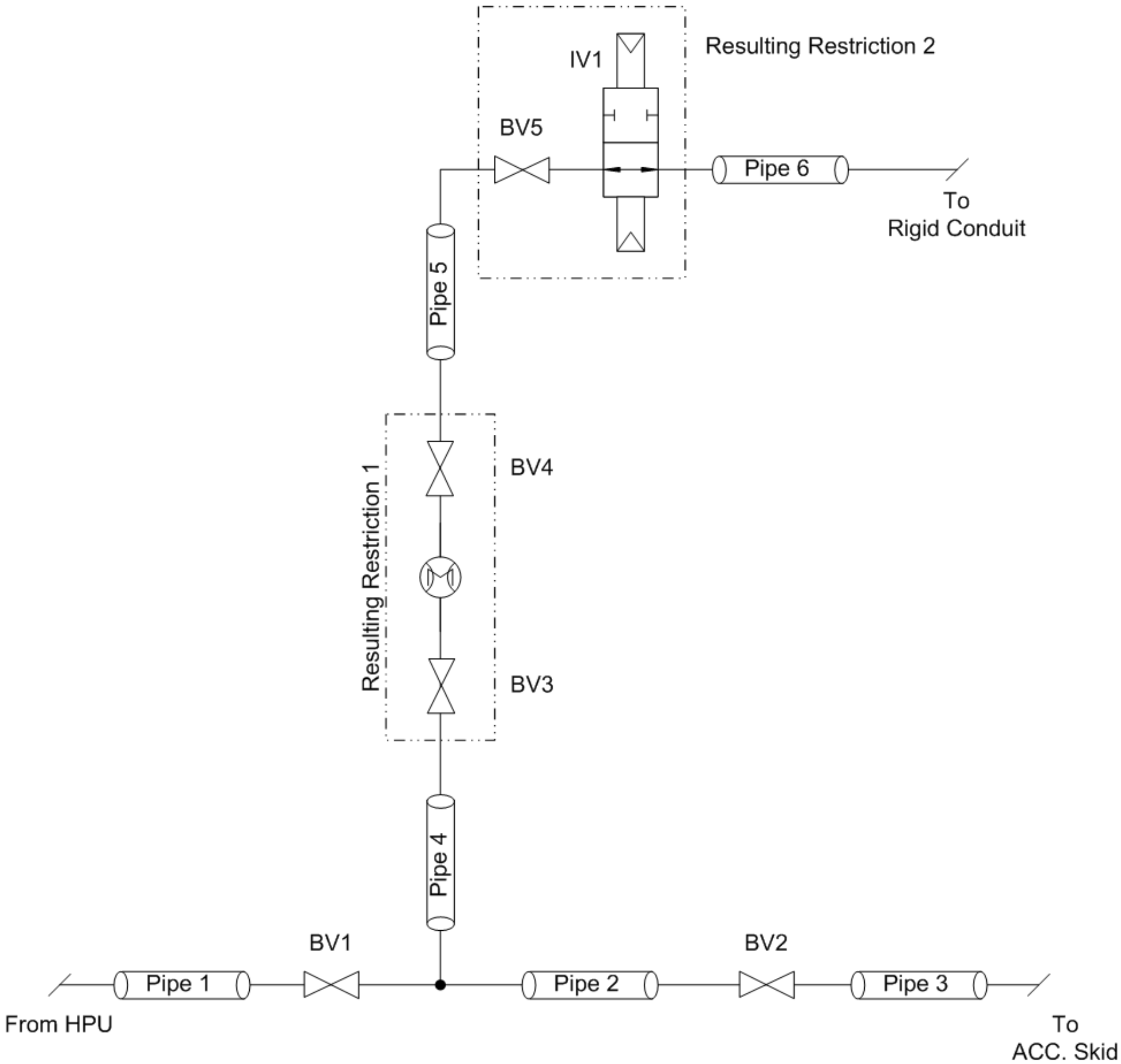


Figure 3. Control Unit schematics

Description	Value	Unit	Reference
Pipe 1: ID 2.575" OD x 0.436 WT Length:	1.503 1	Inch m	Flow Diagram Drawing number SK-122159-21-05 Length estimated
Pipe 2: ID 2.575" OD x 0.436 WT Length:	1.503 2	Inch m	Flow Diagram Drawing number SK-122159-21-05 Length estimated
Pipe 3: ID 2.575" OD x 0.436 WT length	1.503 1	Inch m	Flow Diagram. Drawing number SK-122159-21-05 Length estimated
Pipe 4: ID 2.575" OD x 0.436 WT Length	1.503 1	Inch m	Flow Diagram Drawing number SK-122159-21-05 Length estimated
Pipe 5: ID 2.575" OD x 0.436 WT Length	1.503 1.5	Inch m	Flow Diagram Drawing number SK-122159-21-05 Length estimated
Pipe 6: ID 2.575" OD x 0.436 WT Length	1.503 1.5	Inch m	Flow Diagram Drawing number SK-122159-21-05 Length estimated
2- Way Control Valve N/O Cv		-	
Ball Valves 1 to 5 Cv	480	-	Note 1:
Flow Meter Cv	N/A	-	Meeting 06/24/10
Resulting Cv 1 (used in model): Cv	340	-	Calculated
Resulting Cv 2 (used in model): Cv		-	

Note 1: The estimated Cv values for the ball valves is found on the following web page: www.engineeringtoolbox.com/ball-valves-flow-coefficients-d_223.html

4.4 Accumulator Racks

Need more info about tubing and valves.

Description	Value	Unit	Reference
Surface supply accumulators			
Volume pr. bottle	40	USgal	Meeting 06/24/10
No. off bottles	45	-	Meeting 06/24/10
Pre-charge pressure – N2	2000	psi	Meeting 06/23/10

4.5 Rigid Conduit Line

Description	Value	Unit	Reference
Hose between Rig-tubing and Rigid Conduit Line			
Hose ID	4	in	Email 06/25/10
Hose Length	150	feet	Email 06/25/10
ID hose end fittings		in	
Length of end fittings		in	
Rigid Conduit Line			
Pipe ID (3.5 OD)	2.63	in	Meeting 06/24/10
Pipe Length	5000	feet	Meeting 06/23/10
Hose between Rigid Conduit Line and Rigid Conduit Manifold			
Hose ID	3	in	Email 06/25/10
Hose Length	17	feet	Email 06/25/10
ID hose end fittings		in	
Length of end fittings		in	

4.6 Rigid Conduit Manifold

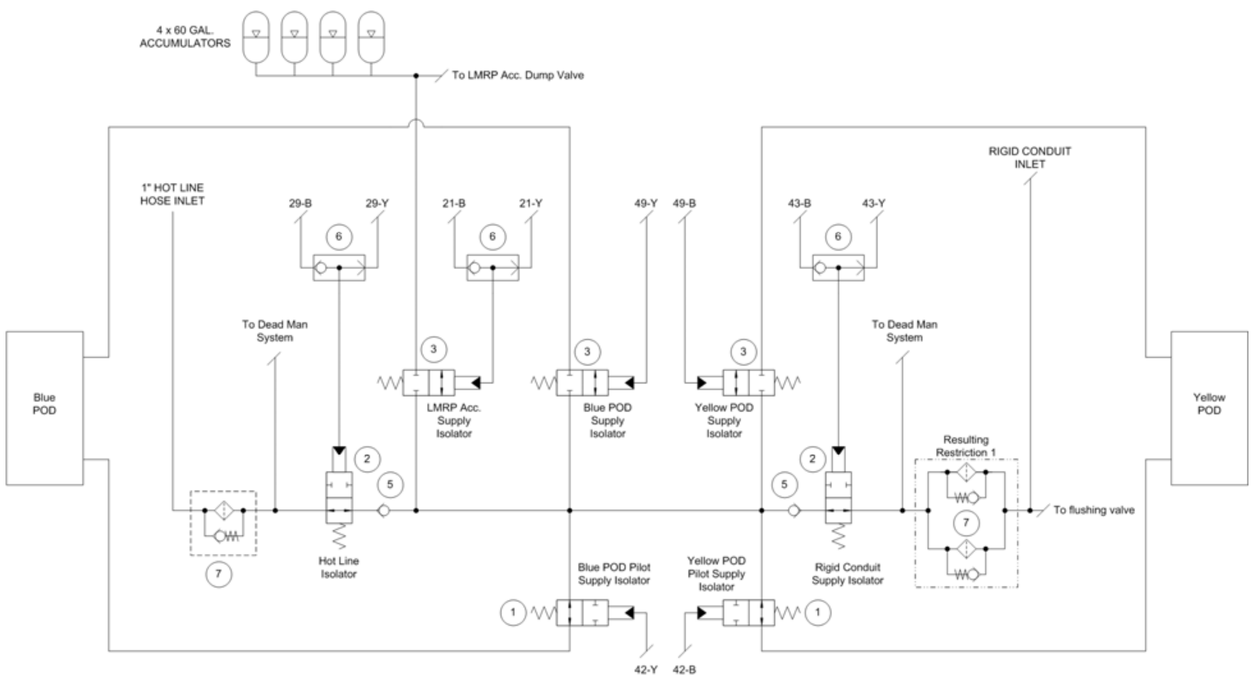


Figure 4. Rigid Conduit Manifold unit schematic

Description		Value	Unit	Reference
NO. 1	SPM Valve ½" N/O OCEANEERING DN.100864			Oceaneering Doc. No. D-0124486
	Cv	3	-	
	Crack To Open Pressure		psi	
	Fully Open Pressure		psi	
	Pilot Consumption		USgal	
NO. 2	SPM Valve 1½" N/O OCEANEERING DN.100813			Oceaneering Doc. No. D-0124486
	Cv	16.3	-	
	Crack To Close Pressure		psi	
	Fully Closed Pressure		psi	
	Pilot Consumption		USgal	

NO. 3 SPM Valve 1½" N/C OCEANEERING DN.100817			Oceaneering Doc. No. D-0124486
Cv	16.3	-	
Crack To Open Pressure		psi	
Fully Open Pressure		psi	
Pilot Consumption		USgal	
NO. 5 Check Valve 1½"			
Cv		-	
Crack To Open Pressure		psi	
Fully Open Pressure		psi	
NO.6 Shuttle Valve ¼ " OCEANEERING DN.100339			
Cv		-	
NO.7 Filter Assy 1 ½ " OCEANEERING DN.0201839			
Cv		-	
Resulting Cv (used in model):			
Cv		-	
LMRP Accumulators			Flow Diagram Drawing number SK-122124-21-05
Total effective gas volume	240	USgal	
Pre-charge pressure for operation on 5000 feet WD	4000	psi	

4.7 Electro-Hydraulic Control Pod

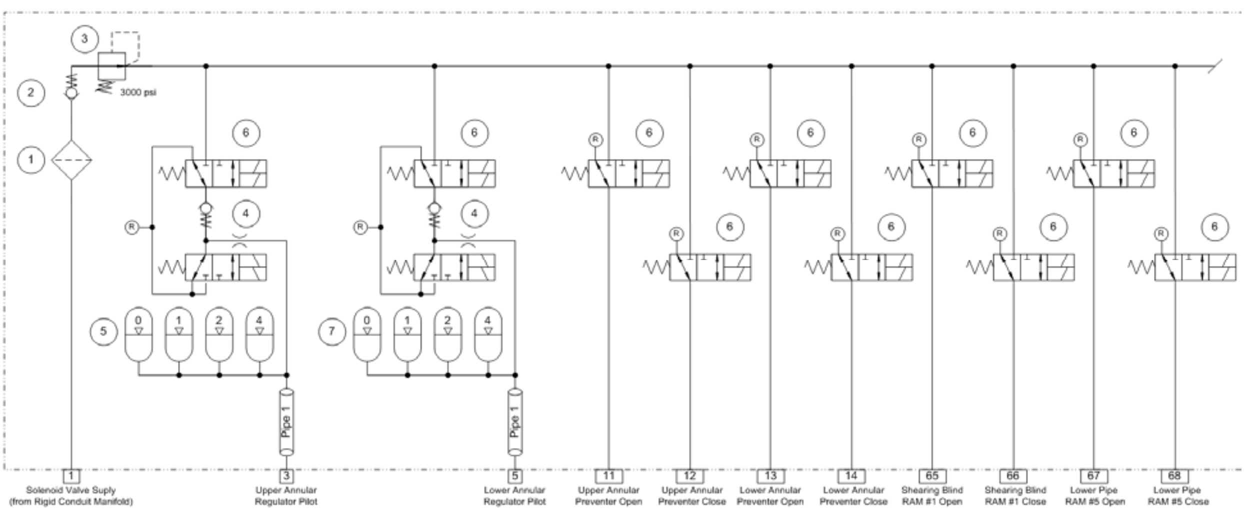


Figure 5. Electro-Hydraulic Control Pod schematic

Description		Value	Unit	Reference
No 2:	Check Valve			
	Cv		-	
	Crack To Open Pressure		psi	
	Fully Open Pressure		psi	
No 3:	¼" Pressure Regulator			
	Cv		-	
	Set Pressure	3000	psi	
No. 4:	Orifice			
	ID	0.06	inch	Estimated

No. 5: Upper Annular Regulator Accumulators			
Effective gas volume	1	USQuart	Meeting 06/24/10
Gas pre-charge pressure 0 for operation on 5000 feet WD	1000	psi	Flow Diagram. Drawing number SK-122108-21-05
Gas pre-charge pressure 1 for operation on 5000 feet WD	1625	psi	
Gas pre-charge pressure 2 for operation on 5000 feet WD	2250	psi	
Gas pre-charge pressure 4 for operation on 5000 feet WD	3500	psi	
NO. 6 1/8" Directional Control Valve - Electrical Operated			
Cv P - A	0.012	-	Meeting 06/24/10
Cv A - T	0.012	-	Meeting 06/24/10
No. 7: Lower Annular Regulator Accumulators			
Effective gas volume	1	USQuart	Meeting 06/24/10
Gas pre-charge pressure 0 for operation on 5000 feet WD	1000	psi	Flow Diagram. Drawing number SK-122108-21-05
Gas pre-charge pressure 1 for operation on 5000 feet WD	1625	psi	
Gas pre-charge pressure 2 for operation on 5000 feet WD	2250	psi	
Gas pre-charge pressure 4 for operation on 5000 feet WD	3500	psi	

4.8 Hydraulic Control Pod – Annular Preventer Control

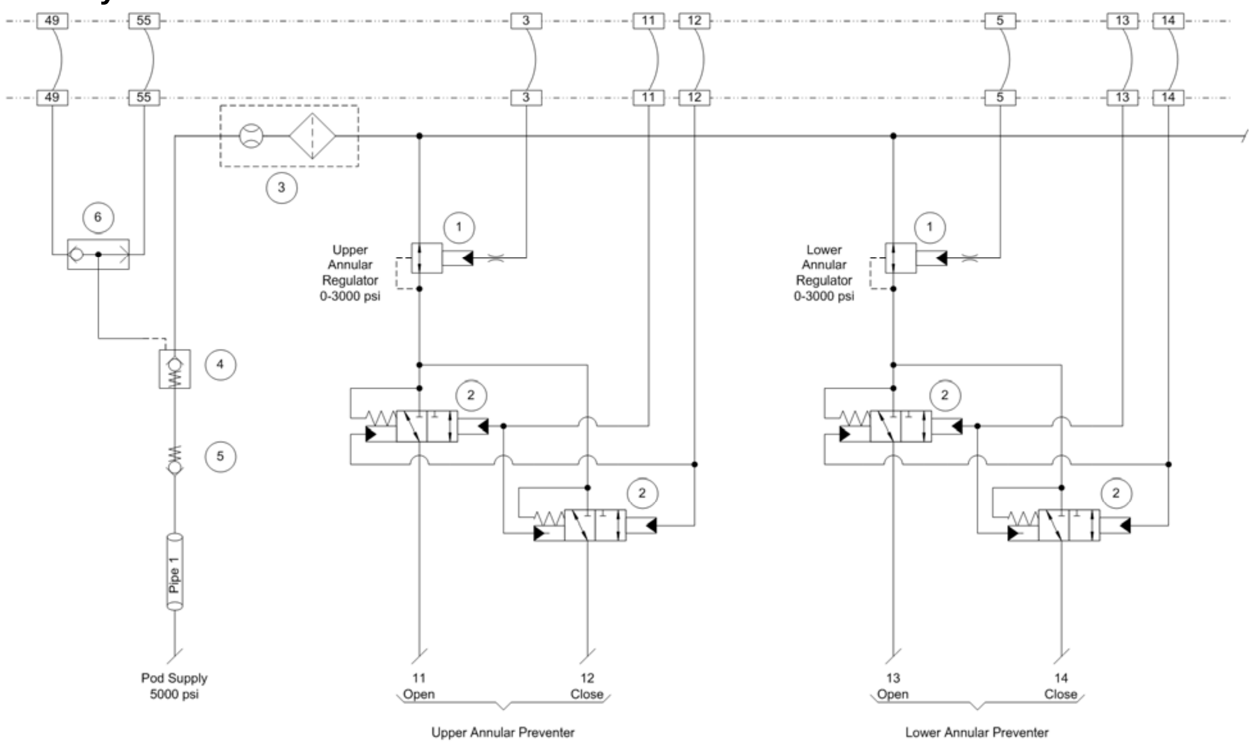


Figure 6. Annular Preventer Control Pod schematic

Description	Value	Unit	Reference
NO. 1 Pressure Regulator			
Cv	30	-	Cameron DWG 309532 rev. E04
NO. 2 Directional Control Valve			
Cv P - A	30	-	Cameron DWG 5k-122462-15 rev. A01
Cv A - T	30	-	
Crack To Open Pressure		psi	
Fully Open Pressure		psi	
Pilot Consumption	1.52	In^3	Calculated
NO. 4 Pilot Operated Check Valve			
Cv		-	
Pilot Ratio	1:2.25	-	Meeting 06/24/10

NO. 5	Check Valve Cv Crack To Open Pressure Fully Open Pressure		- psi psi	
NO.6	Shuttle Valve Cv	22.8	-	Meeting 06/24/10

4.9 Upper and Lower Annular Preventer Controls

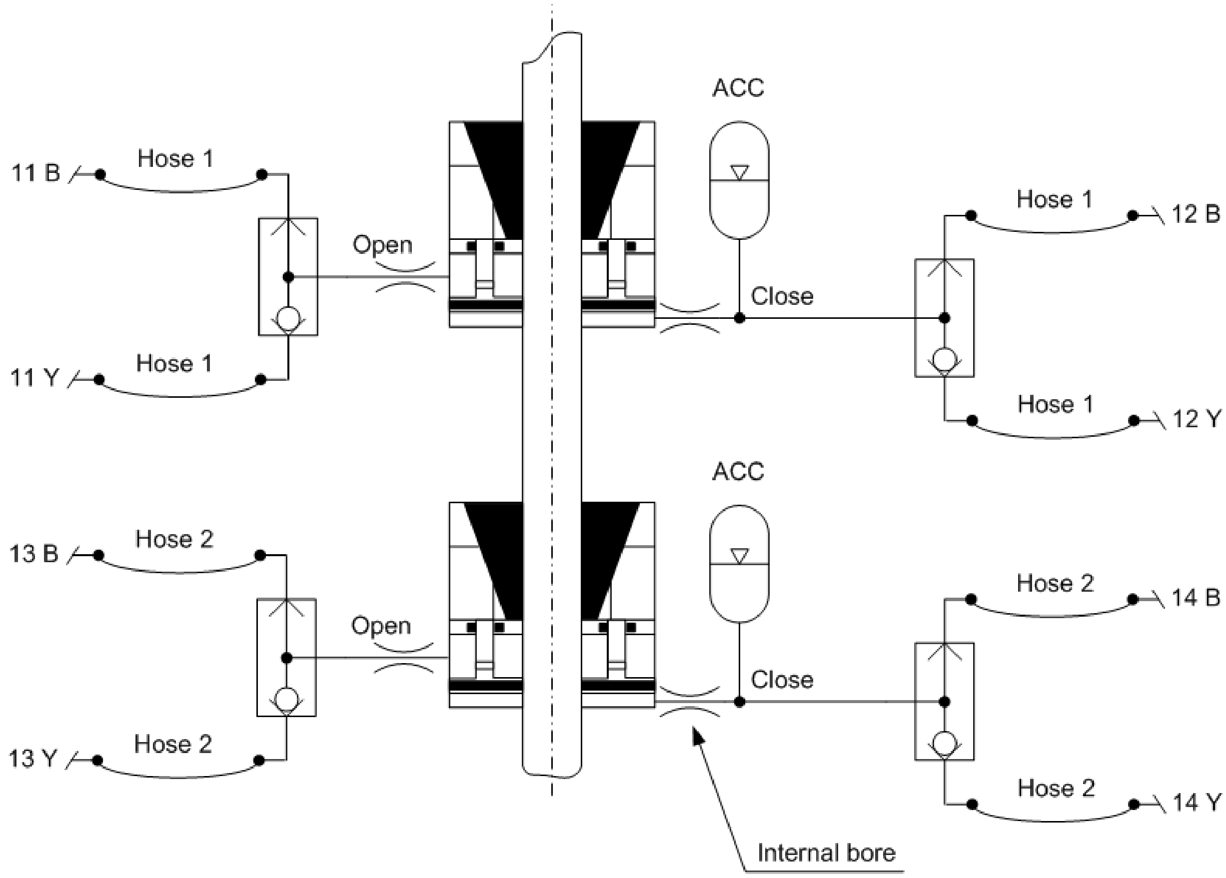


Figure 7. Upper and Lower Annular Preventer

Description	Value	Unit	Reference
Packer Actuators			
Consumption open	51	USgal	Transocean doc. DWH-HSE-PR-001 – section 12 appx. 13
Consumption close	45	USgal	
Start to Open pressure	200	psi	Email 06/25/10
Maximum actuator stroke length	9	inch	Estimated from drawing in Cameron doc. SD017396
Open area	1158.46	Sq.inch	Calculated from volume/stroke
Close area	1308.67	Sq.inch	
Seal elasticity	See section 4.9.1		
Internal bore			
Bore diameter	0.75	In	Estimated
Bore length	15	In	Estimated
Shuttle valve – Gilmore 27030-0.3			
Cv	22.7	-	Meeting 06/24/10
Accumulator			
Effective Gas Volume	15	USgal	Meeting 06/24/10
Pre-charge pressure for operation on 5000 feet WD	2725	psi	Meeting 06/24/10
Hose 1			
ID	1	Inch	Meeting 06/24/10
Length:	15	feet	Meeting 06/24/10
ID hose end fittings	0.5	in	
Length of end fittings	2	in	
Hose 2			
ID	1	Inch	Meeting 06/24/10
Length:	10	feet	Meeting 06/24/10
ID hose end fittings	0.5	in	
Length of end fittings	1	in	

4.9.1 Elasticity in Annular Preventer Seals

Assumptions:

- Packer seals at a volume consumptions of 51 USgal with “Open Hole” and a working pressure of 1500 psi – Ref Cameron Rig Book TC1507 page 3-79.

- Packer seals around a 6 5/8 inch DP at a volume consumption of 46.5 USgal and a working pressure of 1500 psi – Ref BOP tests performed on Well MC 252 Maconda #1 dated 02-10-10 – Lower Annular.

Required volume to close and seal around a 5 ½” DP at 1500 psi is calculated from above to be 47.26 USgal.

It is estimated that the last 3% of stroke is used to squeeze the packer around pipe. The estimated behaviour of the annular element is shown in Figure 8.

This will be updated when FEM analysis of the packer element is ready.

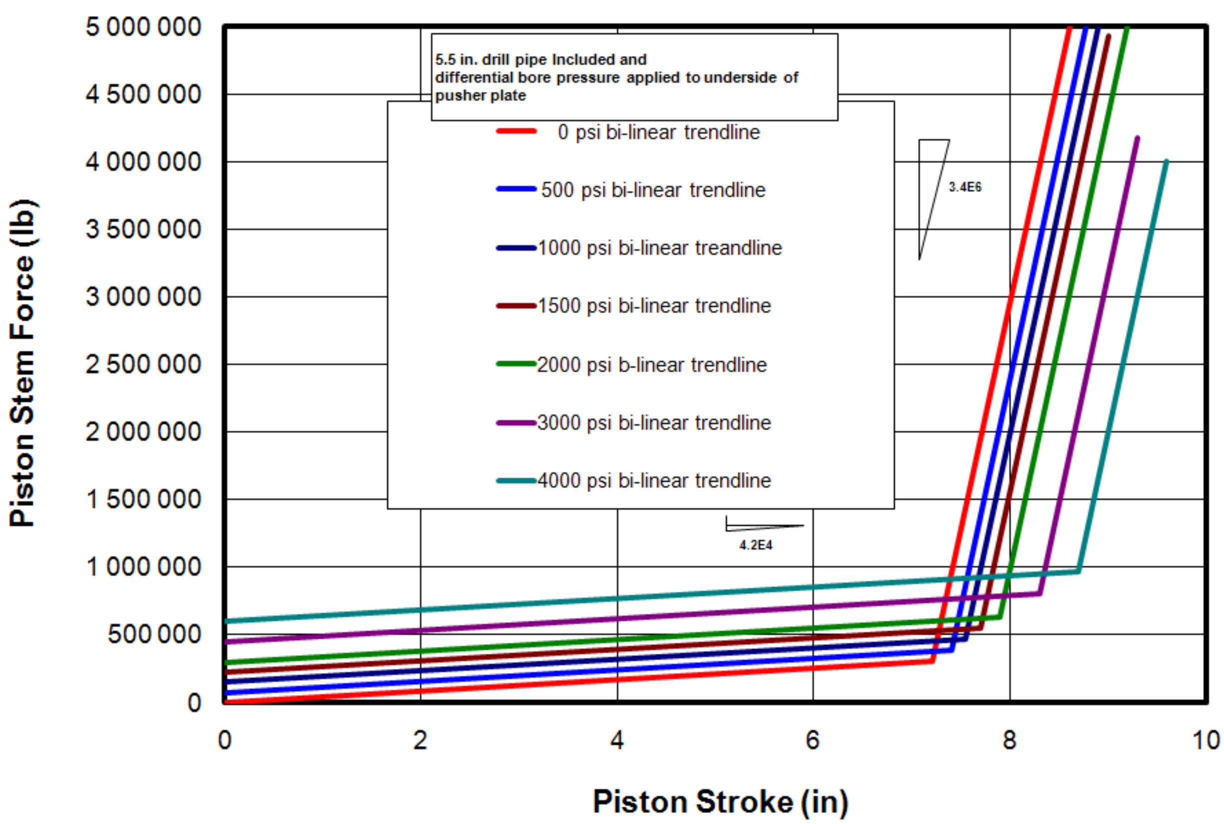


Figure 8. Estimated “Packer Squeeze” curve

4.10 Hydraulic Control Pod - Variable Bore Ram

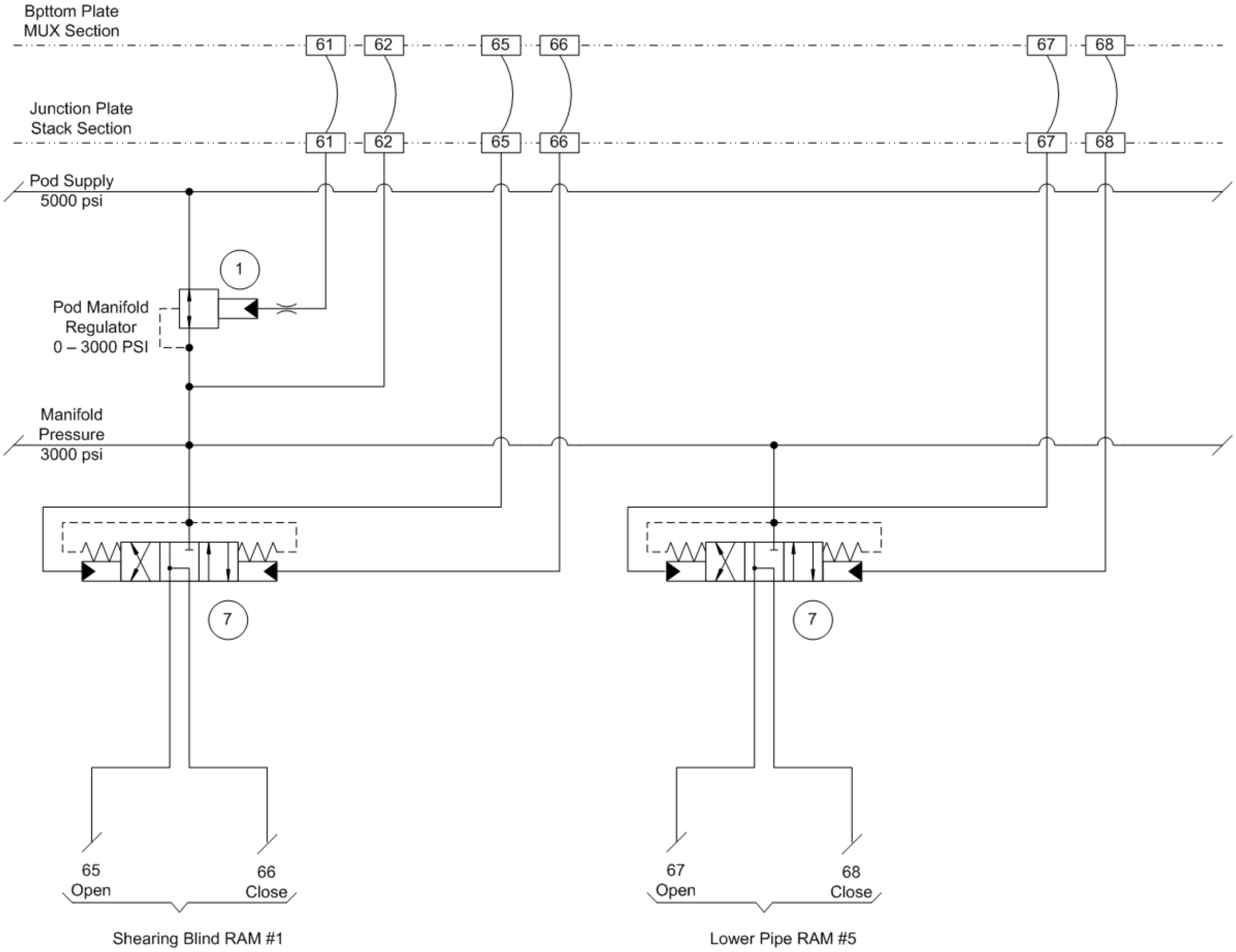


Figure 9. Variable Bore Ram Control Pod schematic

Description		Value	Unit	Reference
NO. 1	Pressure Regulator			
	Cv	30	-	Cameron DWG 309532 rev. E04
NO.6	4-way control valve for VBR control			
	Cv	8	-	Cameron DWG 309530 rev. 01

4.11 Variable Bore Ram

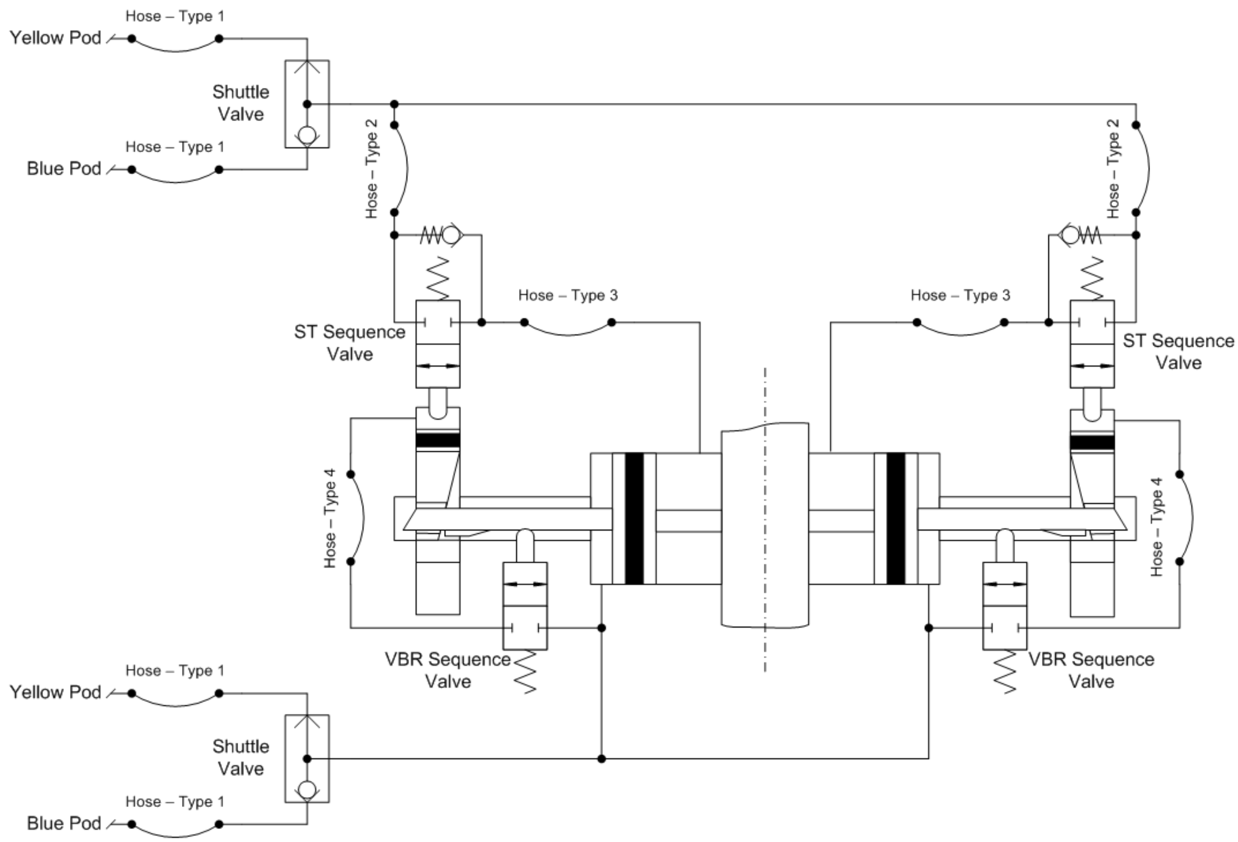


Figure 10. Variable Bore Ram with internal sequence valves

Description	Value	Unit	Reference
Hose – Type 1			
Hose ID	1	in	estimated
Hose Length	50	feet	estimated
ID - end fittings	0.75	in	estimated
Length – end fitting	2	in	estimated
Hose – Type 3			
Hose ID	1	in	estimated
Hose Length	4	feet	estimated
ID - end fittings	0.5	in	estimated
Length – end fitting	2	in	estimated
Hose – Type 4			
Hose ID	1	in	estimated
Hose Length	4	feet	estimated
ID - end fittings	0.5	in	estimated
Length – end fitting	2	in	estimated
Shuttle Valve			
Cv	9	-	Meeting 06/24/10
ST Sequence Valve			
Cv	3	-	estimated
VBR Sequence Valve			
Cv	3	-	estimated

VBR Actuator:			
Volume displacement – Open (one actuator, full stroke)	11.7	USgal	Cameron Rig Book TC1507
Volume displacement – Close (one actuator, full stroke)	12.3	USgal	Cameron Rig Book TC1507
Actuator Closing Ratio	6.7:1	-	Cameron Rig Book TC1507
Full stroke	13.75	in	Calculated
Operating Piston Diameter	17	in	Calculated
Ram Stem Diameter	6.25	in	Calculated
Tail Rod Diameter	5	in	Calculated
ST actuator			
Volume displacement (one ST actuator, full stroke)	3.4	USgal	Cameron Rig Book TC1507